Contact-Free Concept for single-electron Sensitive Large-Mass Detectors

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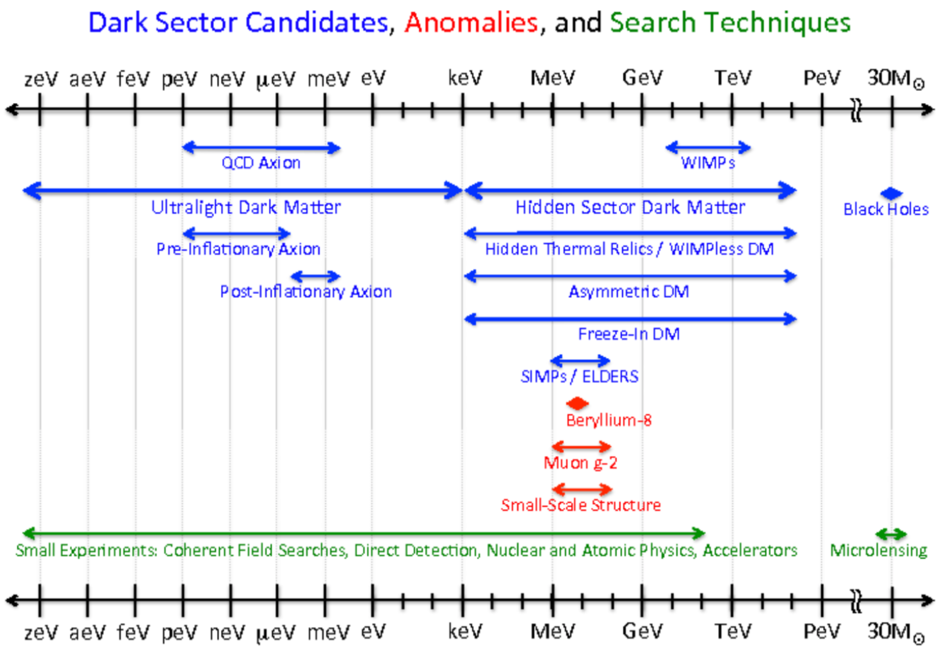
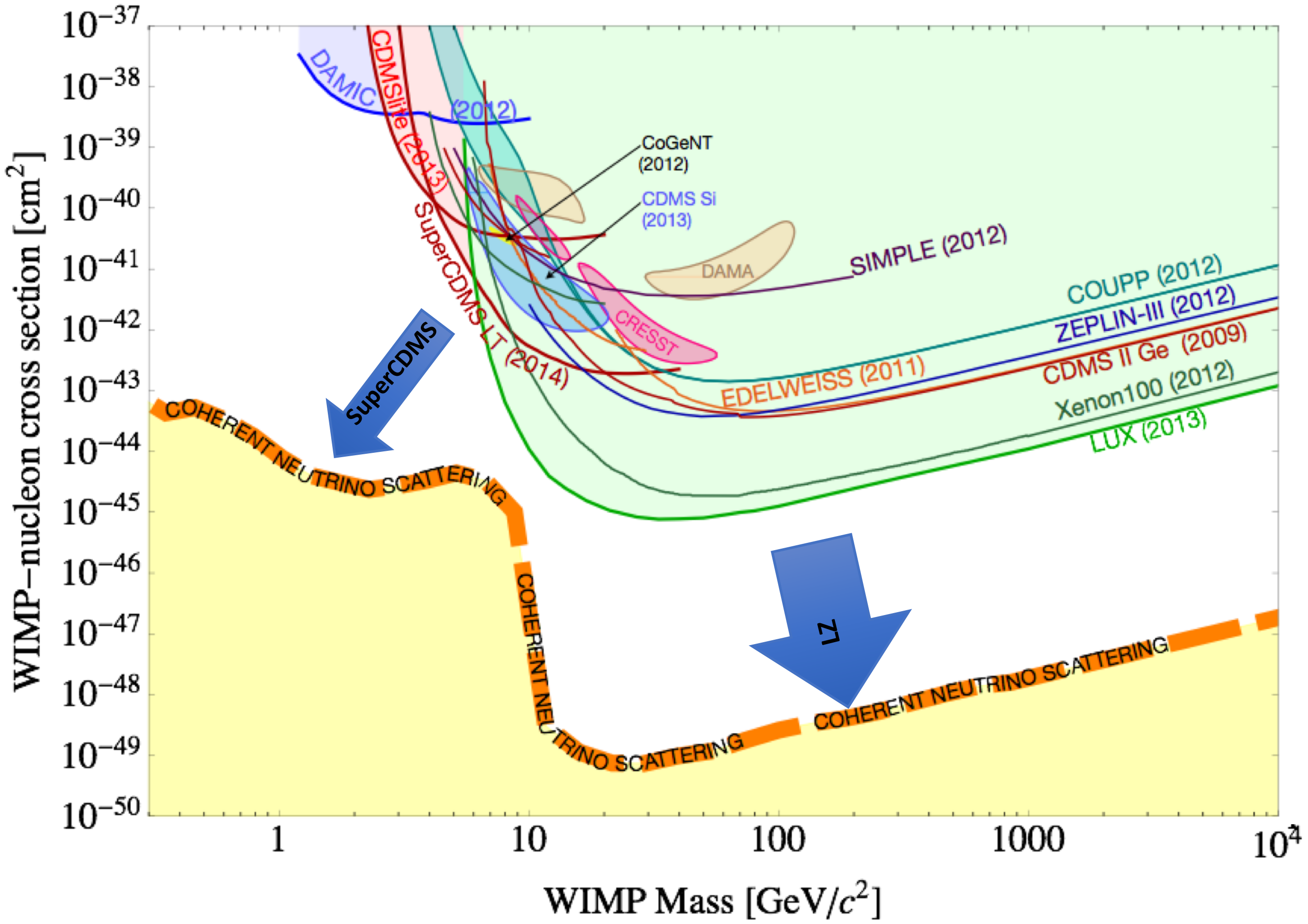
- Common challenge for both DM and CEvNS searches: Low threshold but reasonably large mass detectors.
- Solid state detectors: Good candidates due to the smaller quantum of excitations: Ionization or phonon.
- Low temperature and phonon base detectors: Excellent resolution!
- Carrier drift in phonon mediated semiconductor detectors => Neganov-Trofimov-Luke (NTL) effect.
- Problematic of breakdown and leakage=>Contact-Free bias and readout
- 250 g Ge with near electron sensitivity and 100 g Si detector with single electron resolution: Recently fabricated and demonstrated.
- Perspective.

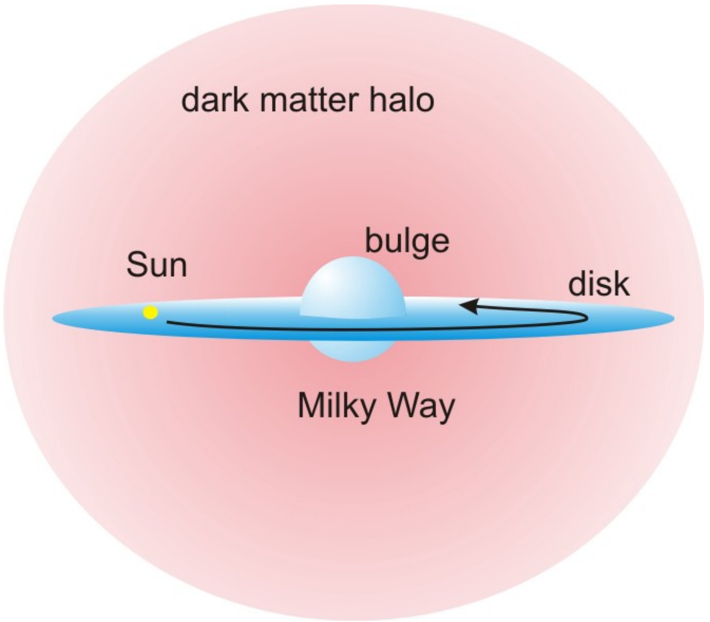
Dark Matter Direct Detection paradigm





Low Mass Dark Matter Detection Challenge

- Dark Matter forming a halo embedding the milky way galaxy.
- DM Particles distribution: Maxwell-Boltzman.
- Density of DM in the vicinity of Solar system ~0.3 GeV/cm^3.
- Escape velocity ~ 650 km/s .



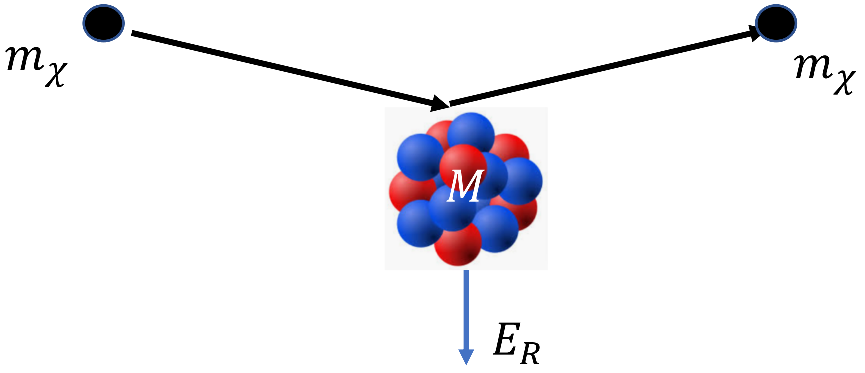
$\rho_\chi = n_\chi m_\chi = cte$ $\quad m_\chi \downarrow \Rightarrow n_\chi \uparrow \Rightarrow$ Larger signal rate

$E_\chi = \frac{1}{2} m_\chi v^2$ Maxwell-Boltzam=>v is independent of the mass

$$E_R \propto E_\chi \frac{m_\chi M}{M + m_\chi} \qquad m_\chi \ll M \qquad E_R \propto m_\chi^2$$

$$\frac{\partial^2 R}{\partial E_r \partial \Omega_r} = \frac{\rho_0 \sigma A^2}{4\pi m_\chi \mu_{\chi n}^2} \times F^2(E_r) \hat{f}_{\text{lab}}(v_{\min}, \hat{\boldsymbol{q}}_{\boldsymbol{r}}; t)$$

$$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190 \text{ eV} \times \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$



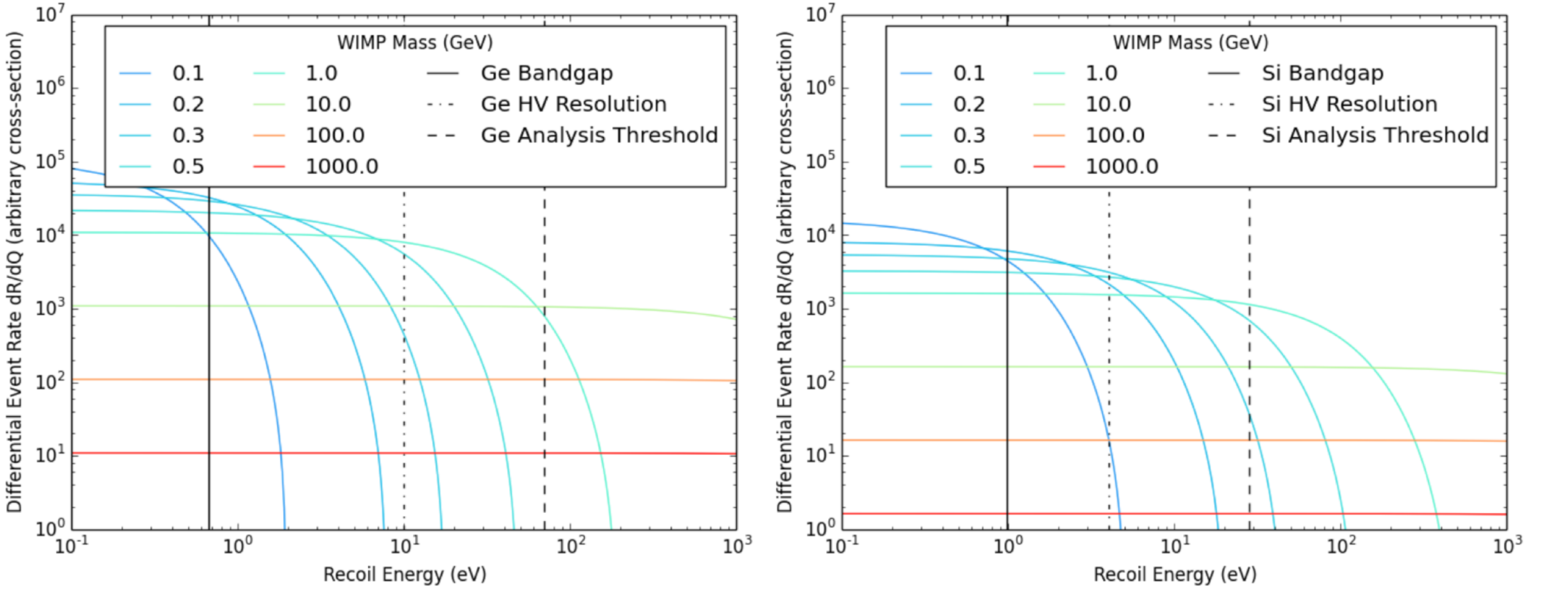
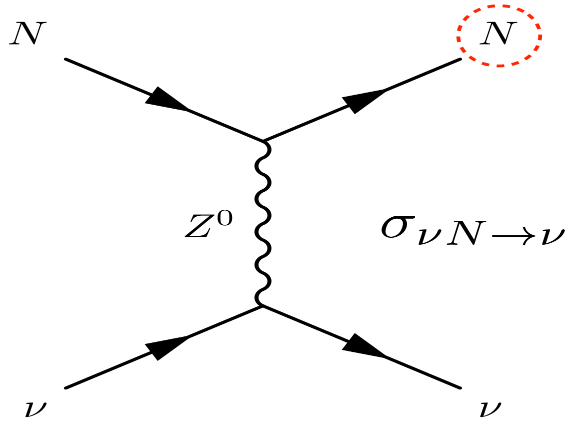


Figure 1: Recoil energy spectra for dark matter of various masses for the standard spin-independent WIMP-like coupling, assuming Maxwell-Boltzmann velocity distribution centered on 220 km/s mean velocity. Left is the rate in Ge, right in Si. The event rate is less in Si due to the lower atomic weight for the same number density and nucleon cross-section, but the lighter nucleus means there is less kinematic suppression for Si, and thus lower masses can be probed with the given phonon energy thresholds.

Kurisnky et al., https://arxiv.org/pdf/1611.04083.pdf

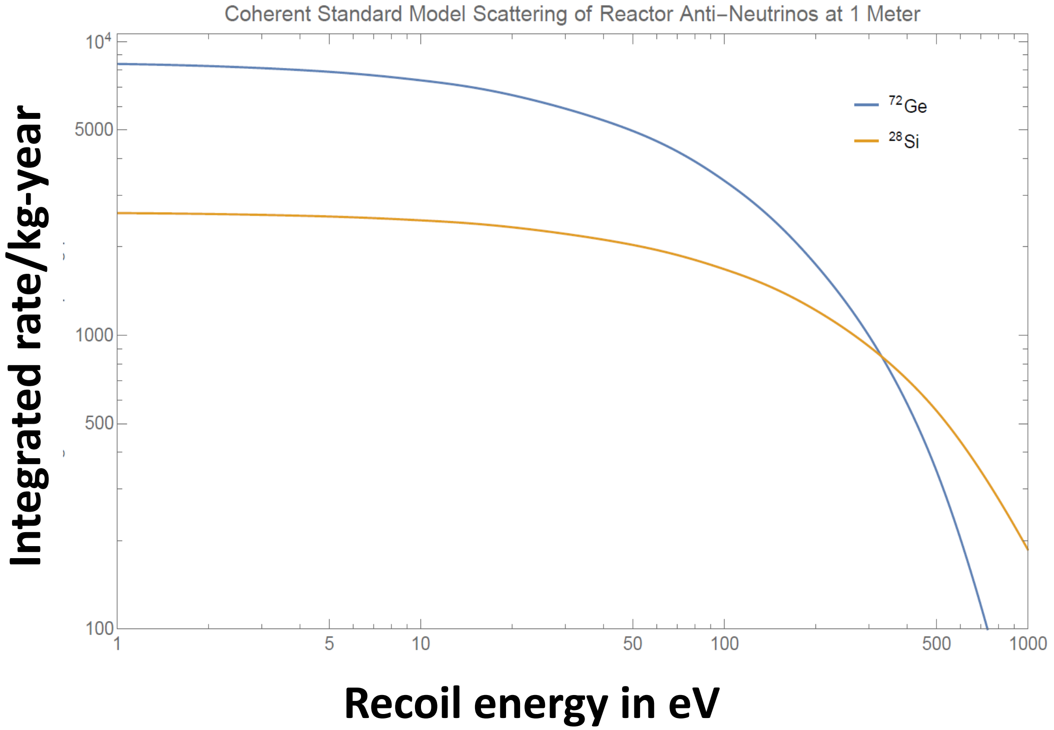
Coherent Elastic Neutrino-Nucleus Scattering ($CE\nu NS$)



$$\sigma_{\nu N \to \nu N} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2$$

Flavor-blind Standard Model process

$\sigma_{\bar{\nu} N \to \bar{\nu} N}$	E_ν=3MeV
Ge	$6.0\times10^{-41}cm^2$
Ar	$1.8\times10^{-41}cm^2$
Si	$7.4\times10^{-42}cm^2$

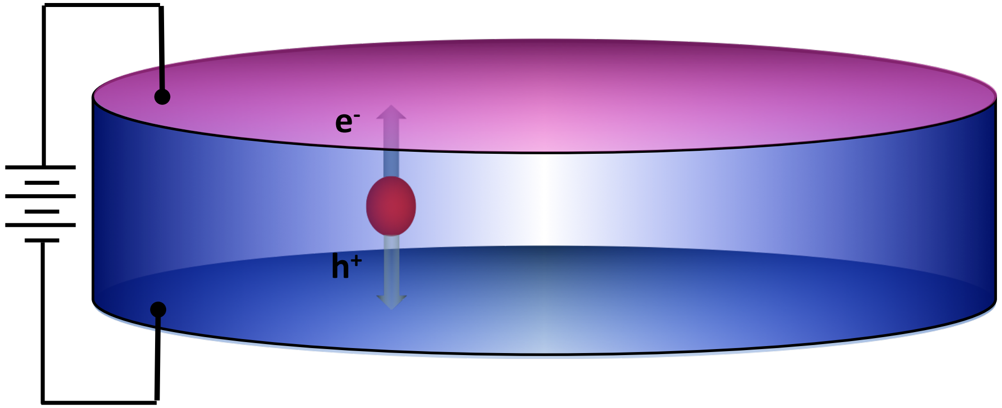


Excellent tool to probe BSM Physics, but never been utilized due to lack of low threshold detectors

Can detect CENNS in ~ 1month

Direct Ionization measurement in SC detectors

- Measure Ionization directly with a charge amplifier.
- Detectors operate at T< carrier freeze out => No need for depletion
- Need Cold front end close to the detector : HEMT/FET.
- S/N degrades with the input capacitance.
- Limited by noise associated with high impedance readout:
  - FET or HEMT input noise.
  - Microphonics.
  - EM Pickups.
  - Ground loops…
- Best electronics RMS achieved with CDMS detectors: ***σ*~200 eV$_{ee}$**
- Recently with HEMT front-end ***σ*~70 eV$_{ee}$**



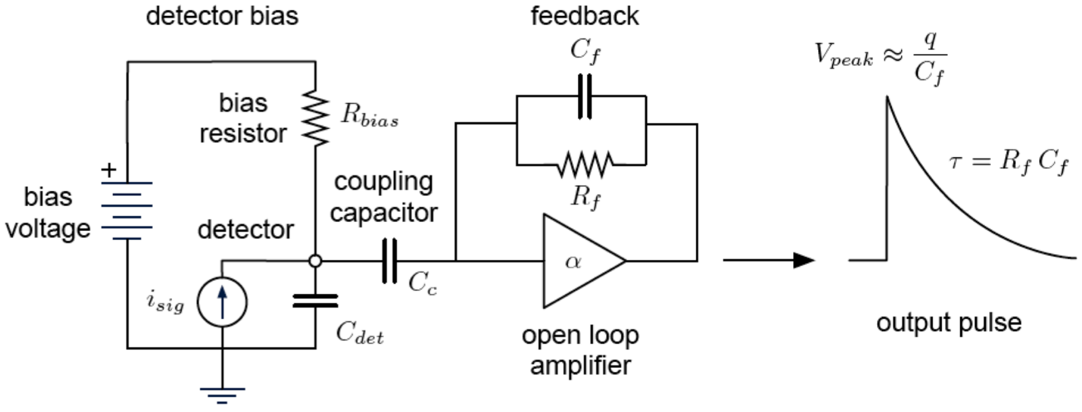


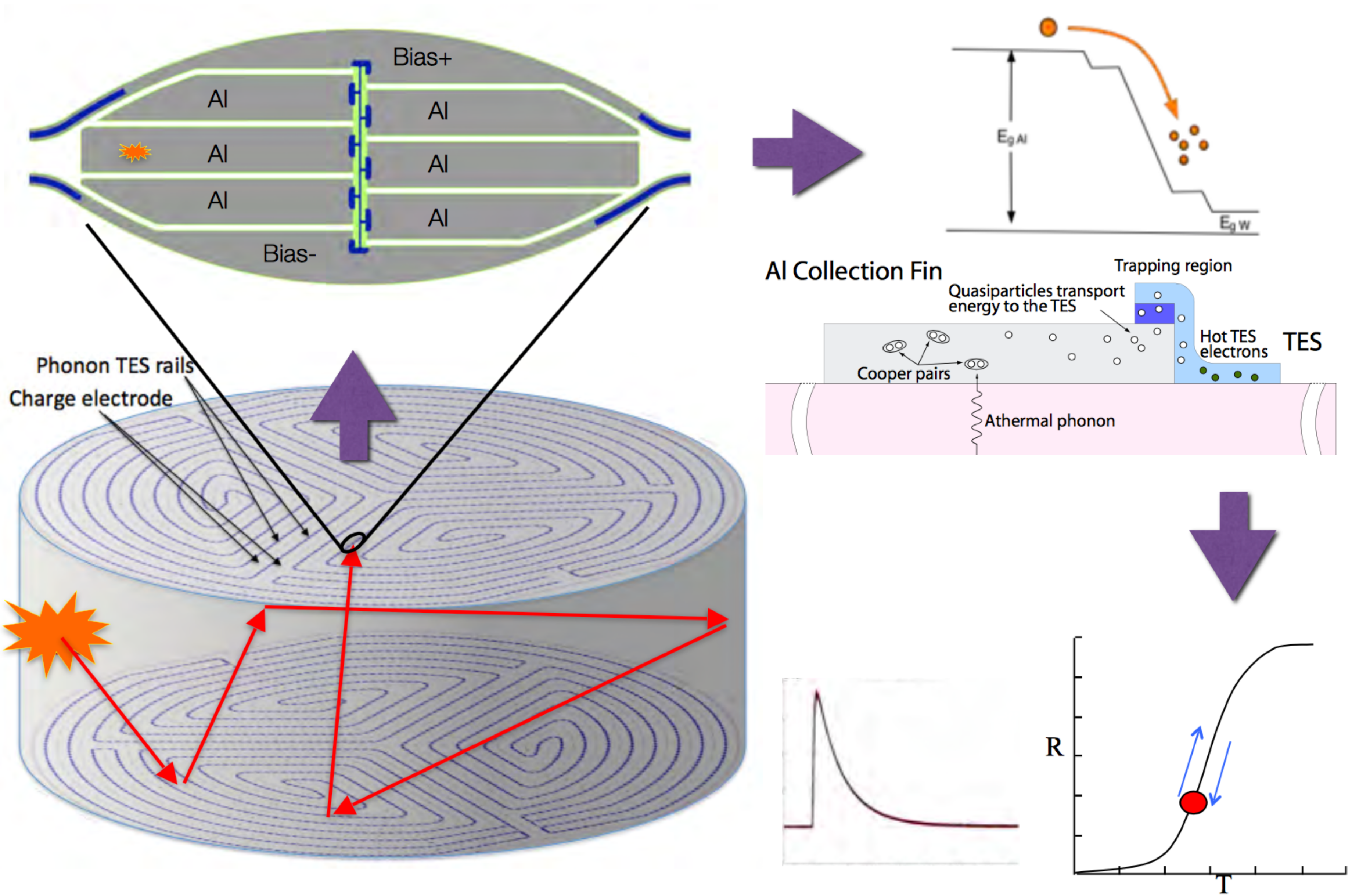
Figure 3.4: The basic charge amplifier topology.

From Arran Phipps thesis, UC Berkeley, Spring 2016

Low Noise Phonon readout

- Phonons among the lowest quantum excitations in condense matter detectors.
- Tremendous progress in low noise phonon readout down to fraction of eV for small calorimeters.
- Almost detector mass independent for athermal phonon measurement.
- Phonon measurement => No Quenching factor!
- Measure phonons directly or use Neganov-Trofimov-Luke effect to indirectly measure ionization down to e-h resolution.

Athermal Phonon Readout: CDMS technology



Neganov-Trofimov-Luke Effect: Indirect Ionization measurement using phonons

Power=V.I or Energy=V.Q

- **Luke**-Neganov Gain

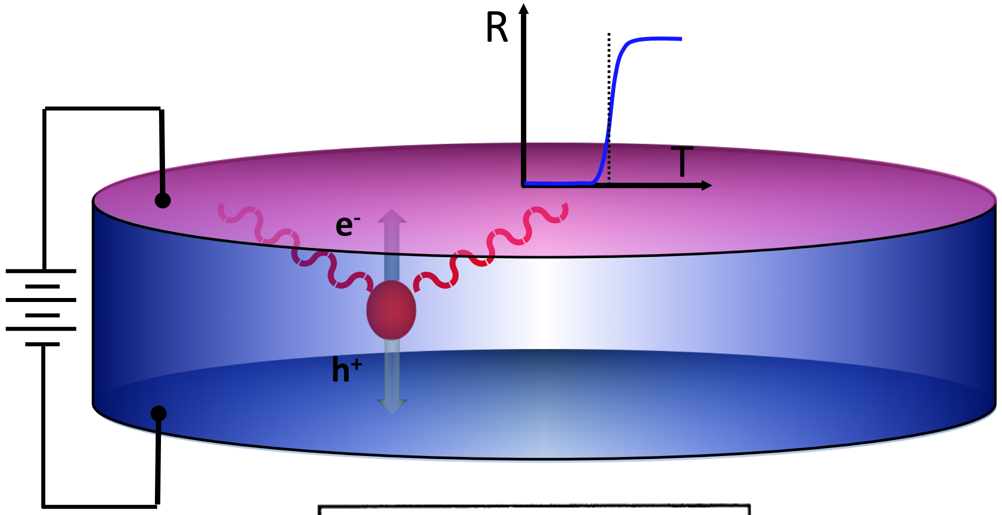
$$
\begin{aligned}
E_{tot} &= E_r + E_{luke} \\
&= E_r + n_{eh} e V_b \\
&= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)
\end{aligned}
$$

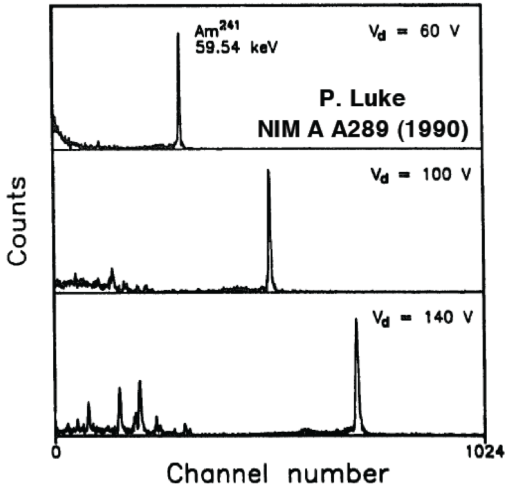
- Phonon noise doesn't scale with the ionization bias:

=> **S/N ⇧**

- In theory one can increase Bias to reach Poisson fluctuation limit!

limitation: Current leakage

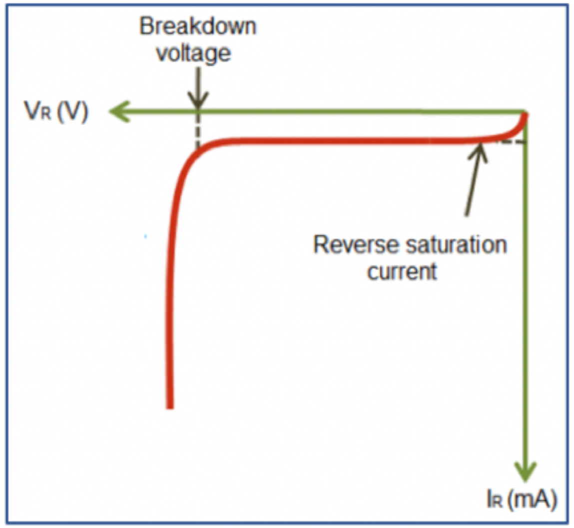


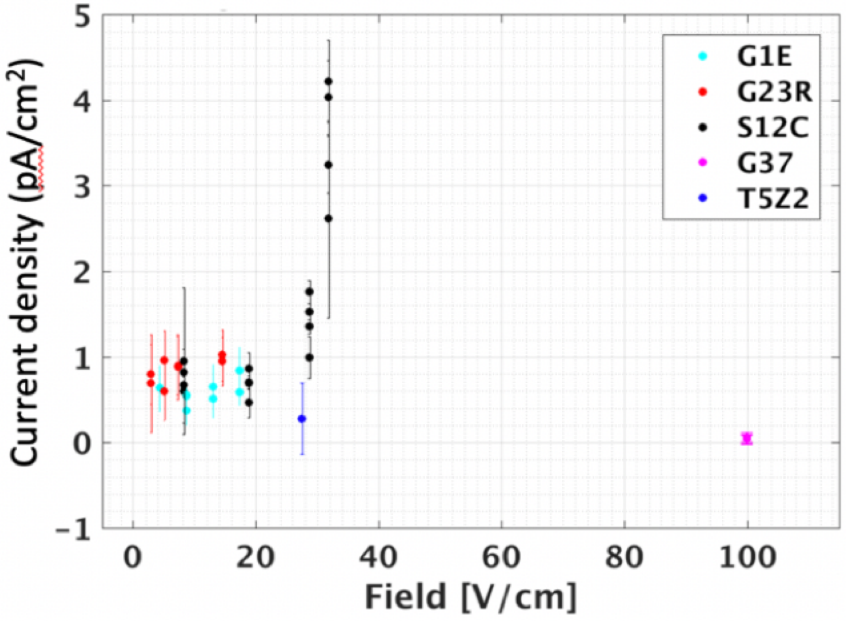


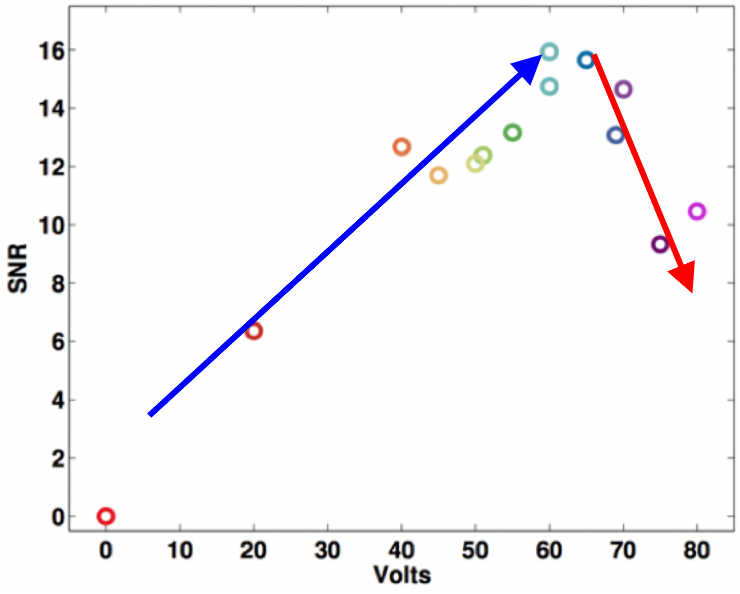
Luke et al., Nucl. Inst. Meth. Phys. Res.A 289, 406 (1990)

Limitation: Breakdown or leakage

- CDMS HV detectors exhibit a behavior much like a diode in reverse bias:
  - A small but constant leakage ~ 10^{-14}-10^{-13} A up to a threshold voltage.
  - Above the threshold sudden increase in leakage.
- The NTL gain => Better S/N but up to the bias where $\sigma_{electronics} < \sigma_{leakage}$.
- For a constant $I_{leakage}$ both signal and noise scale with V so above $\sigma_{electronics} \sim \sigma_{leakage}$ no further gain in S/N. The S/N plateaus.
- When detector breaks down=> S/N degrades with V.





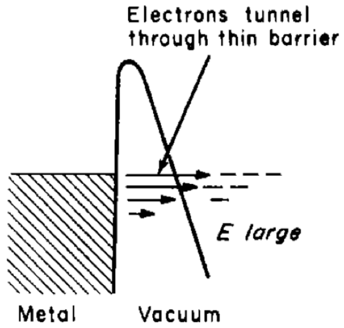


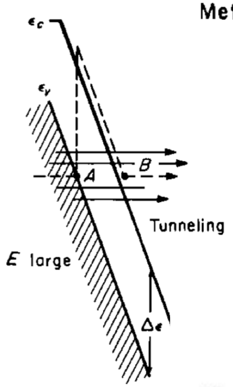
Ritoban Thakur Ph.D. thesis

Need to study ”breakdown”!

- What causes the breakdown at such low fields?
- Impact ionization on impurities:
  - Ionized
  - Neutral
- Leakage through electrodes?
- Conduction over detector free surface:
  - Better surface treatment?
  - Common problem if surface damaged.

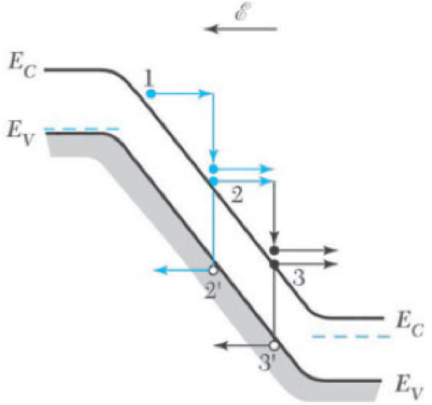
Injection through contact by tunneling



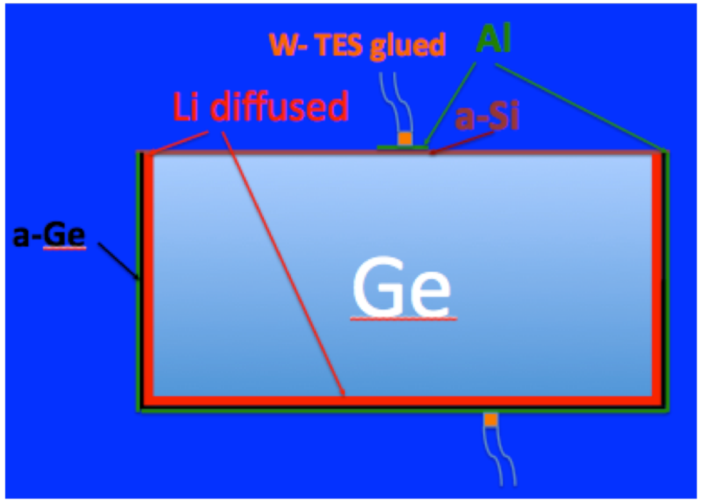


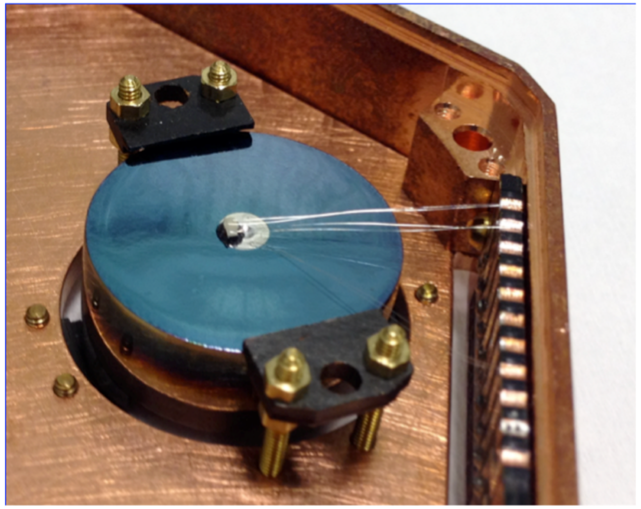
J.P. McKelvey, Solid-state and semiconductor physics, Harper & Row, 1966.S.M. Sze, Semiconductor devices: physics and technology, 2nd Ed., Wiley, 2002.

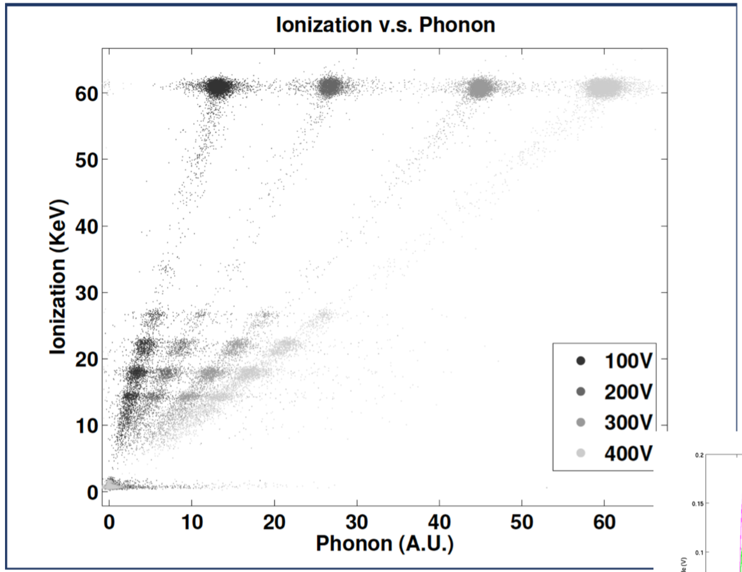
Avalanche

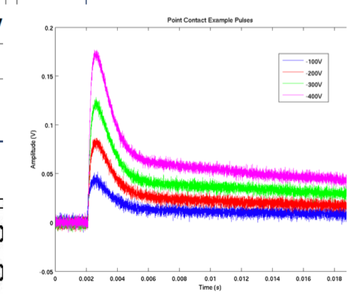


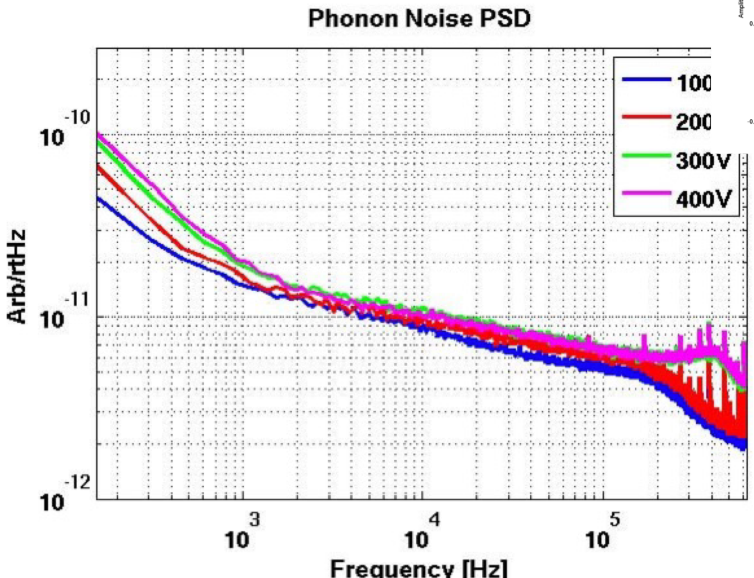
PPC @ 77 K sustains much larger Field:
What about a sub Kelvin PPC?







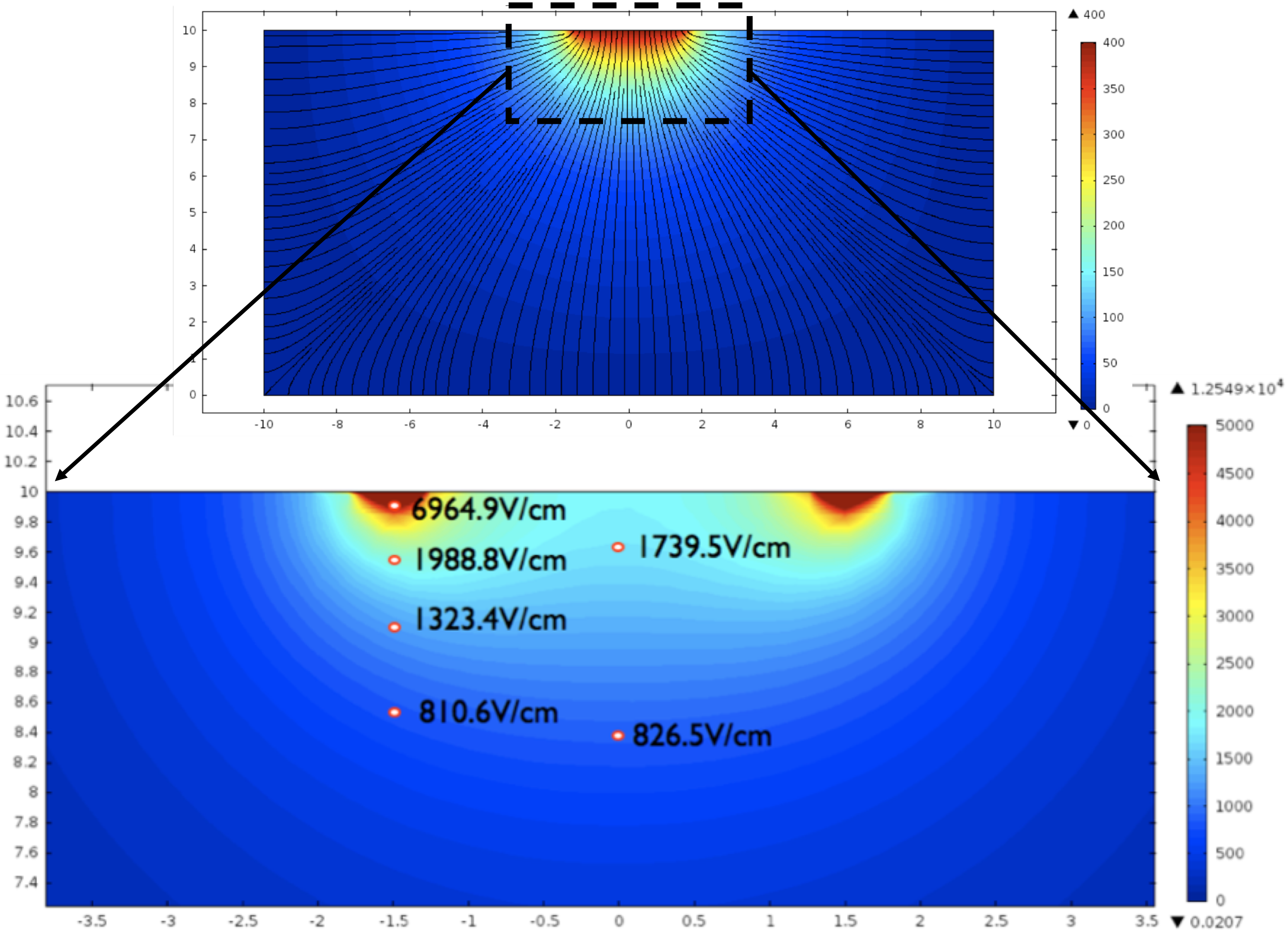




- A small PPC prepared for ionization and phonon readout.
- No fast leakage obsereved up to 400 Volts.
- In the vicinity of the point contact the field can be > 2000 V/cm
- No intrinsic break down.
- Also charge seems to be stable at large V's.
- The resolution too poor to assess slow leakage.

N. Mirabolfathi et al., J. Low T. Phys. 176, 209-215 (2014).

E Field in PPC for V_{bias}=400Volts



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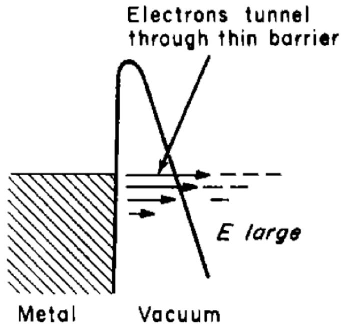
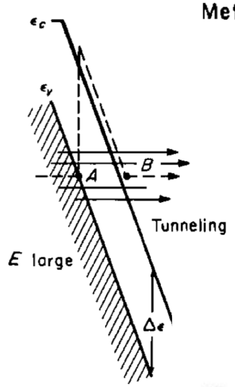
Injection through contact by tunneling





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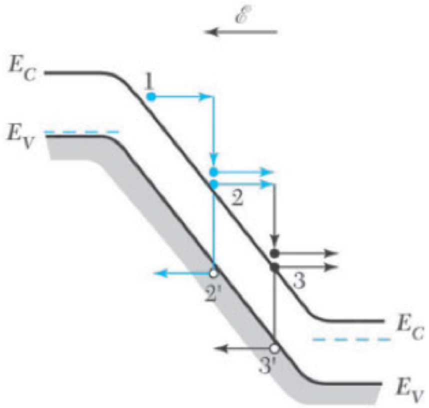
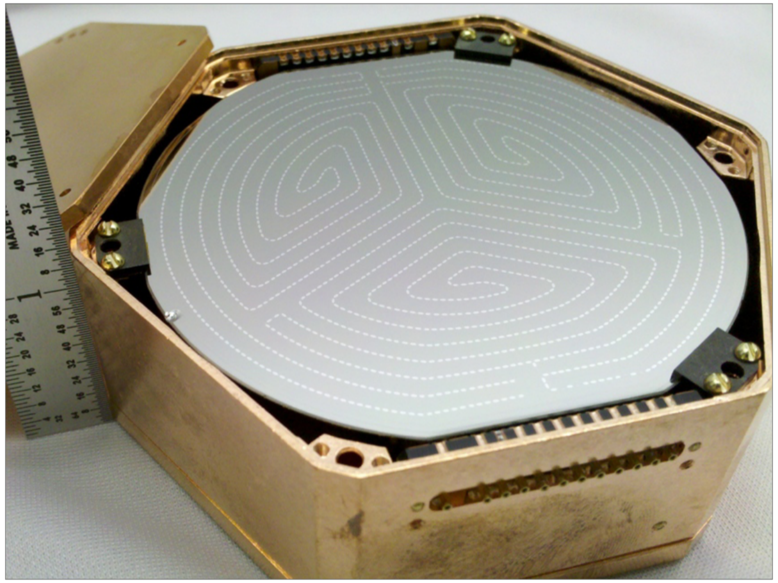
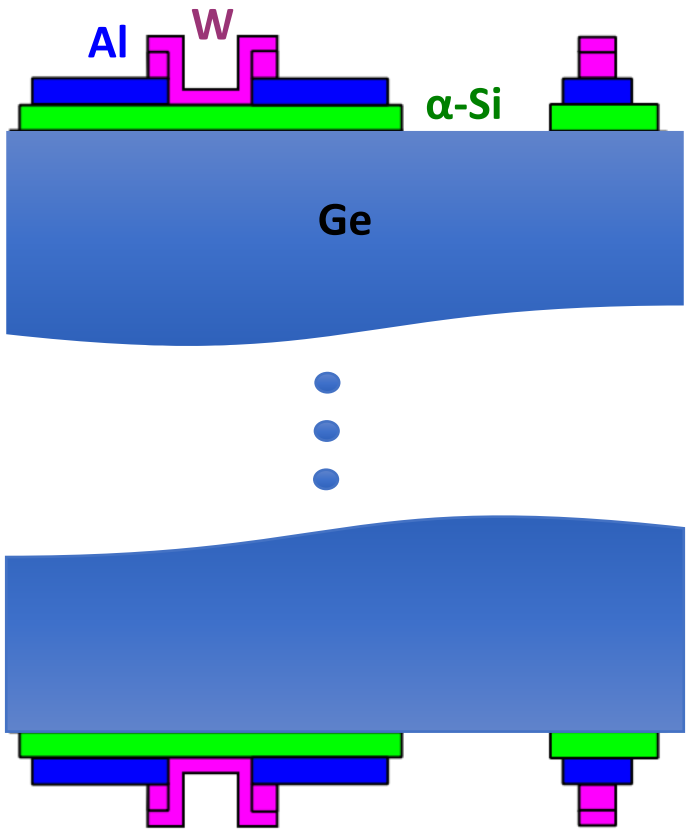


CDMS symmetric contact geometry

- Both faces of the detector uniformly covered with sensors.
- Metal-crystal interface symmetric on both faces of the crystal
- Unable to characterize a leakage assisted by the interface: Tunneling, pinning …

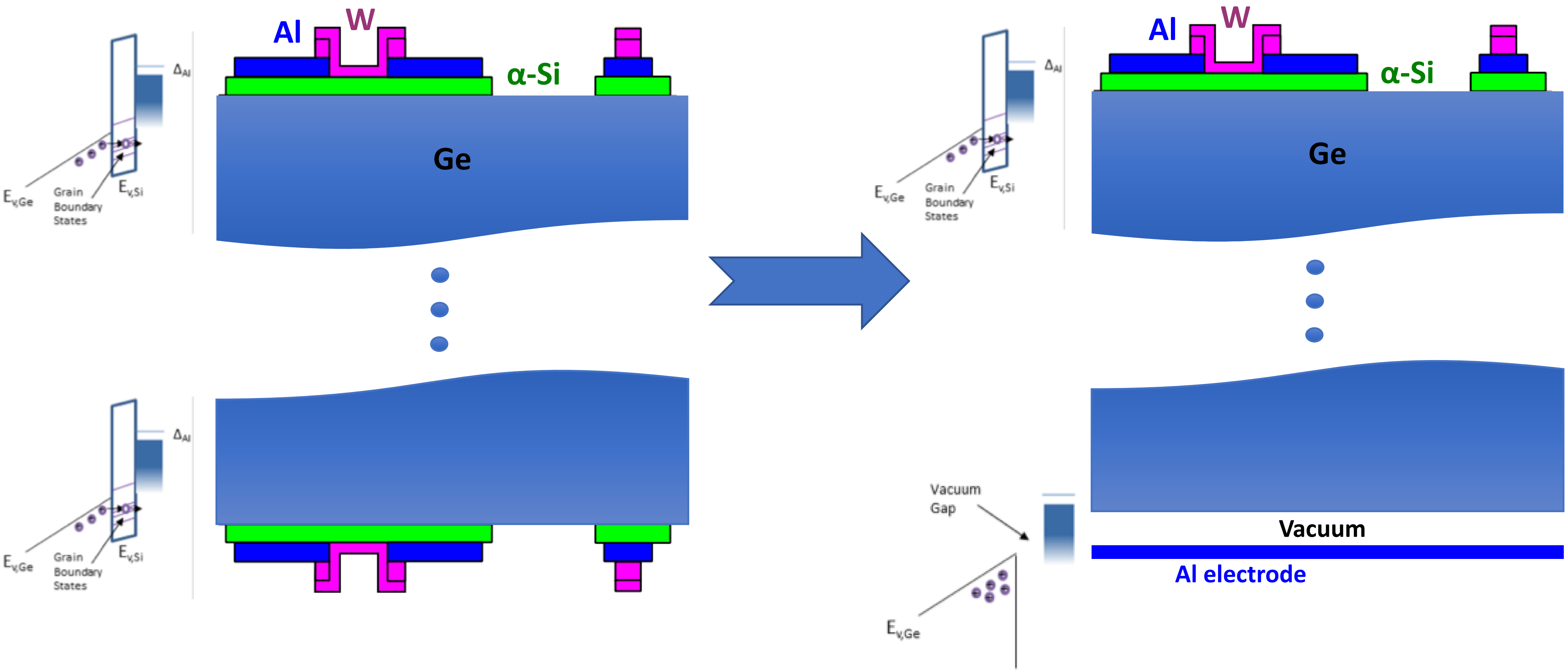




In CDMSlite mode only readout one face phonon sensors. The other face used for biasing.

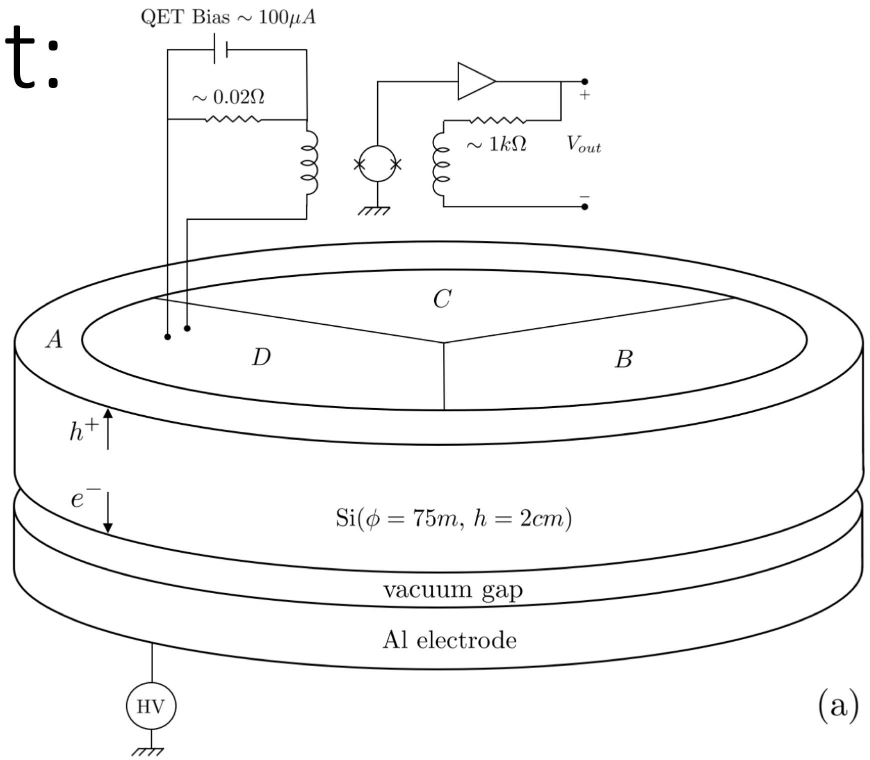
N.Mirabolfathi et al. Nucl.Instrum.Meth.A 855 (2017), 88-91

CDMSlite symmetric contact geometry



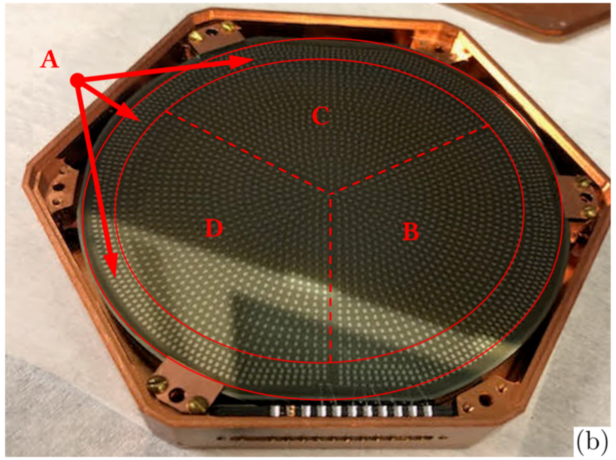
N.Mirabolfathi et al. Nucl.Instrum.Meth.A 855 (2017), 88-91

High Voltage phonon readout: Contact-Free Bias

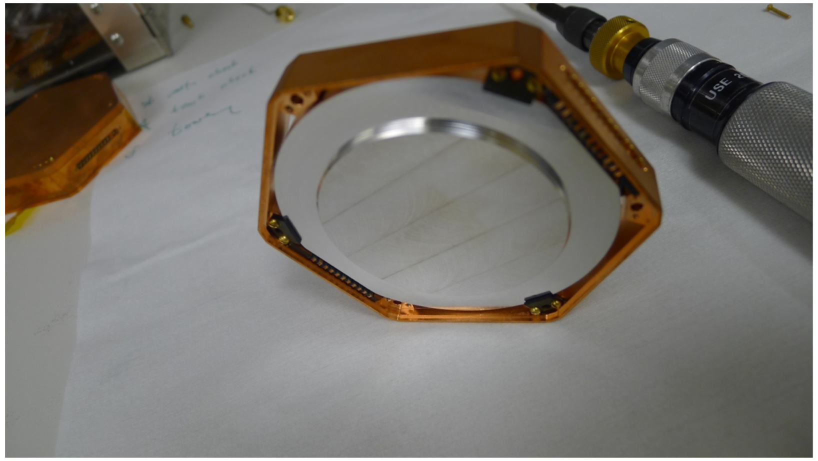


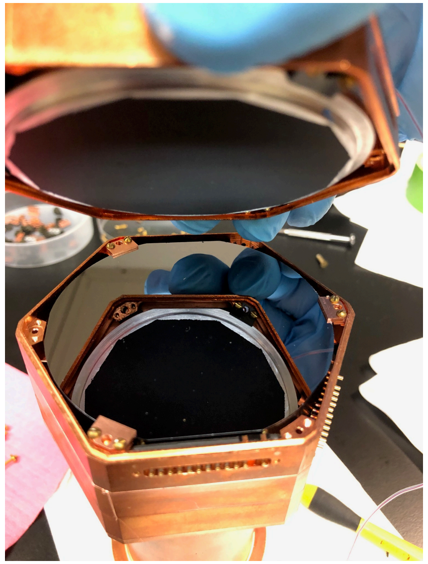
(a)

- One face of the detector processed with CDMS style phonon sensors
- Fully covered by Four W based athermal phonon readouts.
- The opposite face left polished and bare.
- Bias the detector through a gap ~ 0.5 mm
- Carriers gradually accumulate under the contact-free electrode.
- Neutralize with a flash of LED.

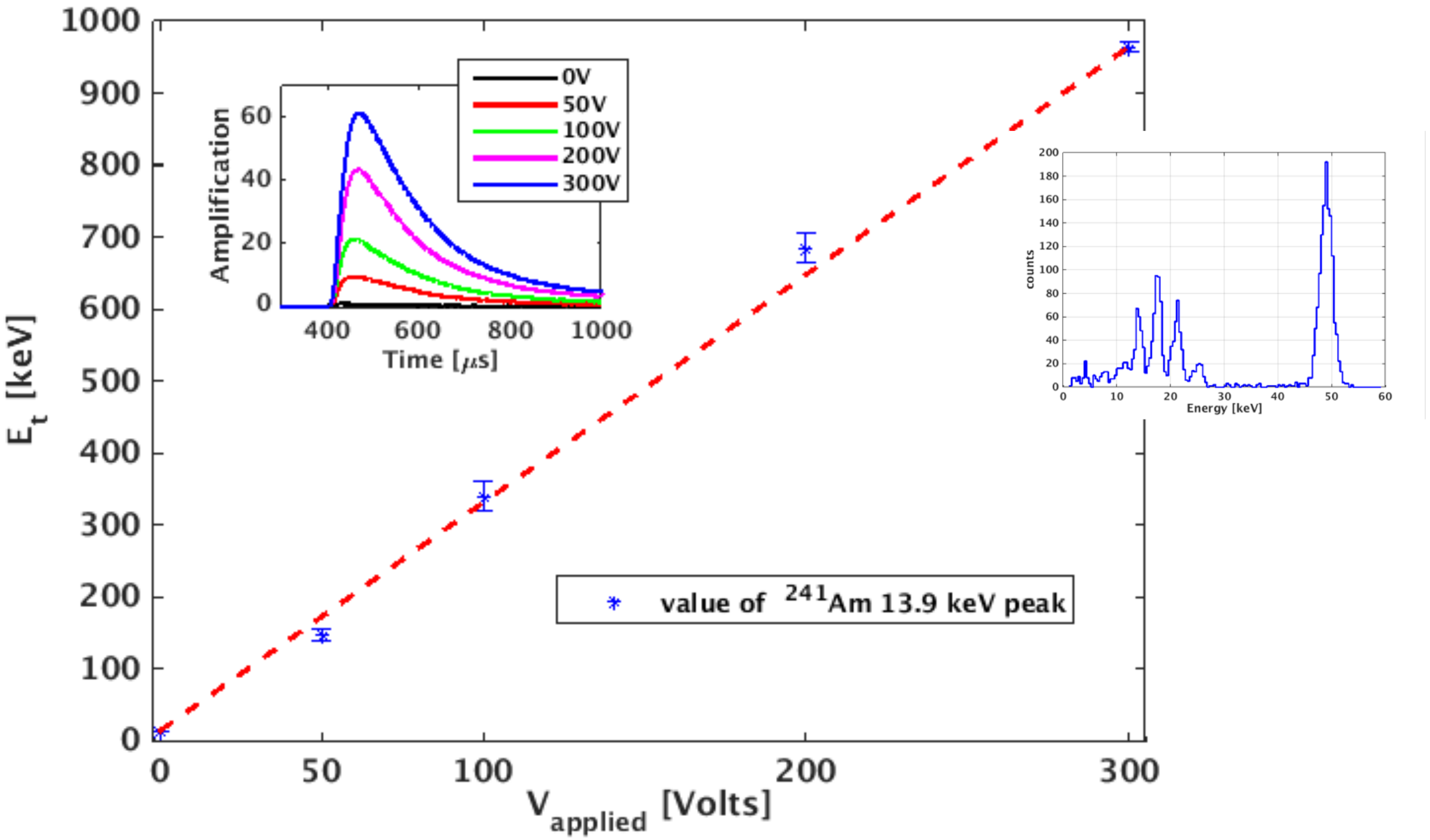


(b)



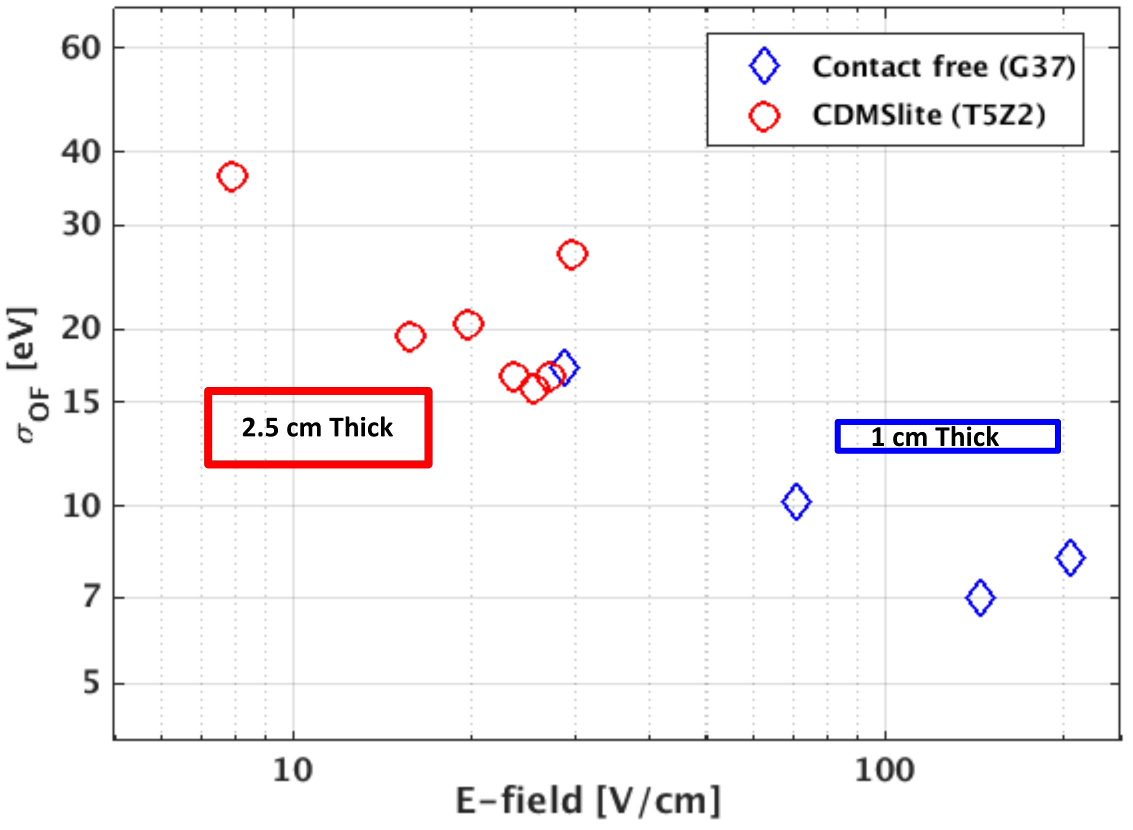


Contact Free performance:
Ge **Φ**=75 mm h=10 mm (250 g)



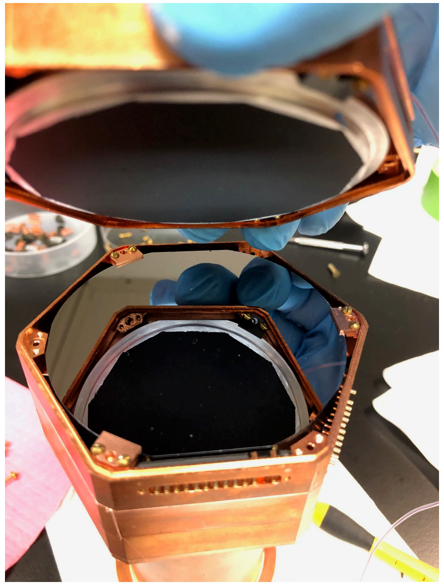
N.Mirabolfathi et al. Nucl.Instrum.Meth.A 855 (2017), 88-91

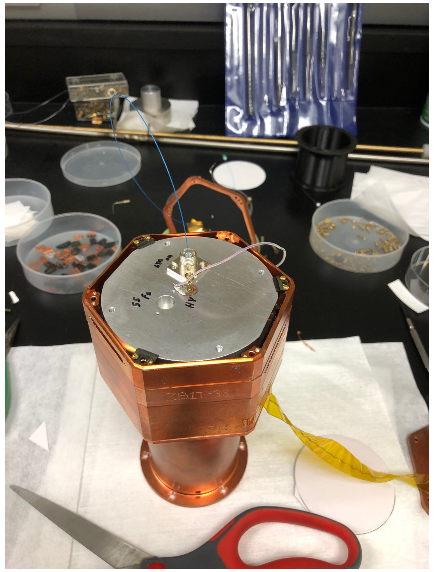
Comparing Contact free and CDMSlite

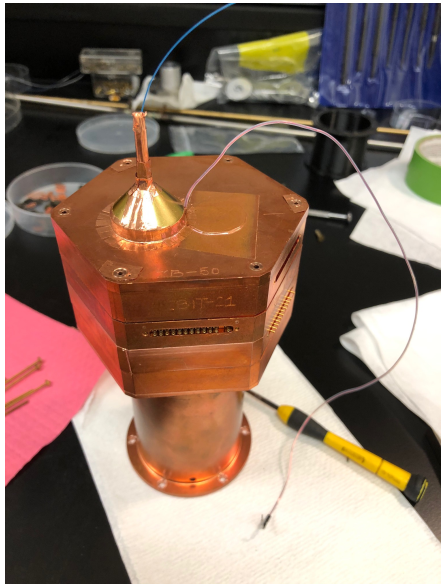


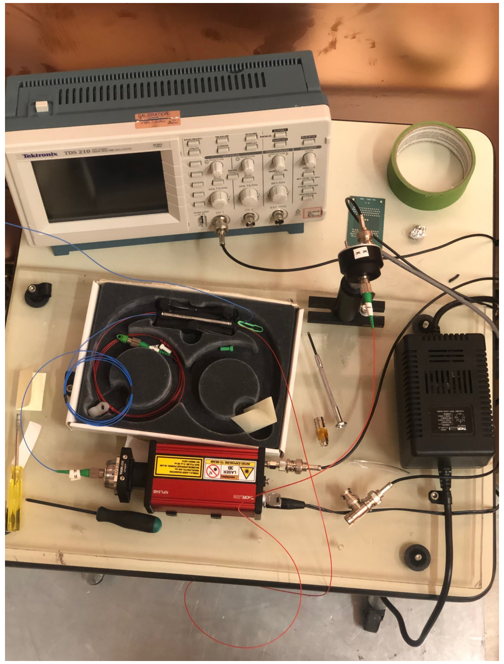
N.Mirabolfathi et al. arXiv:1510.00999

Laser photon and fiber optics setup at TAMU

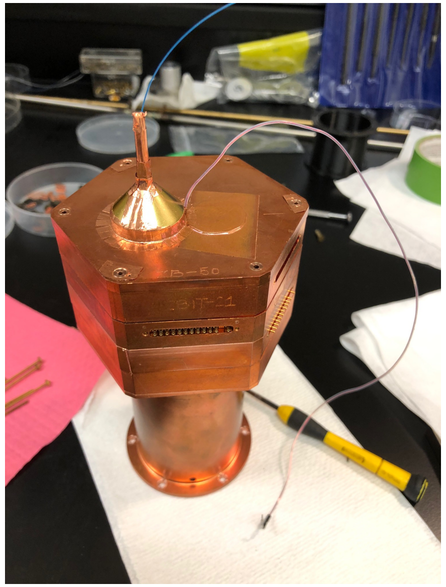


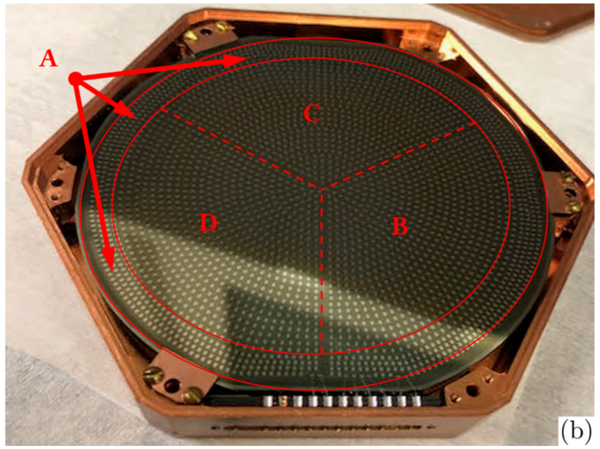


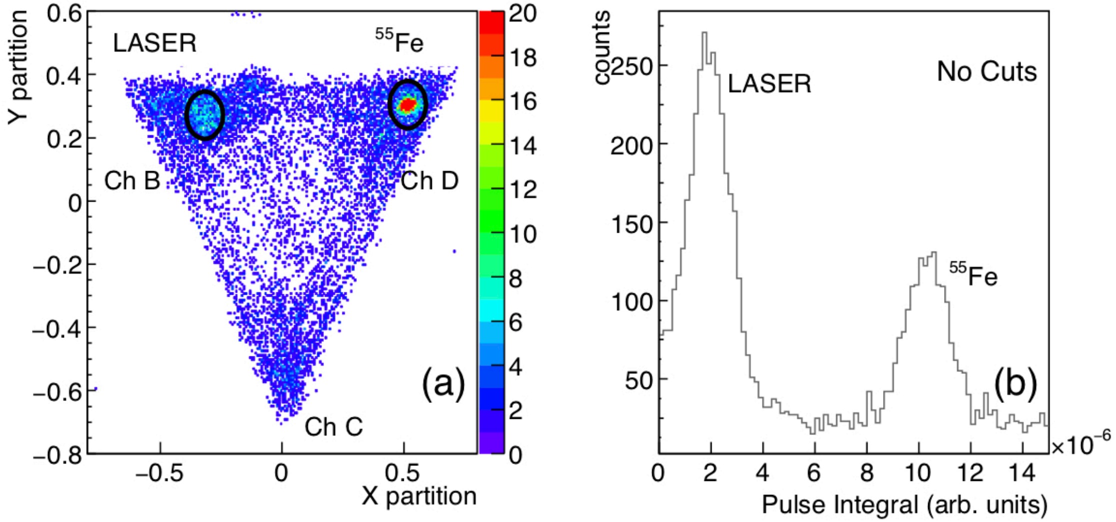


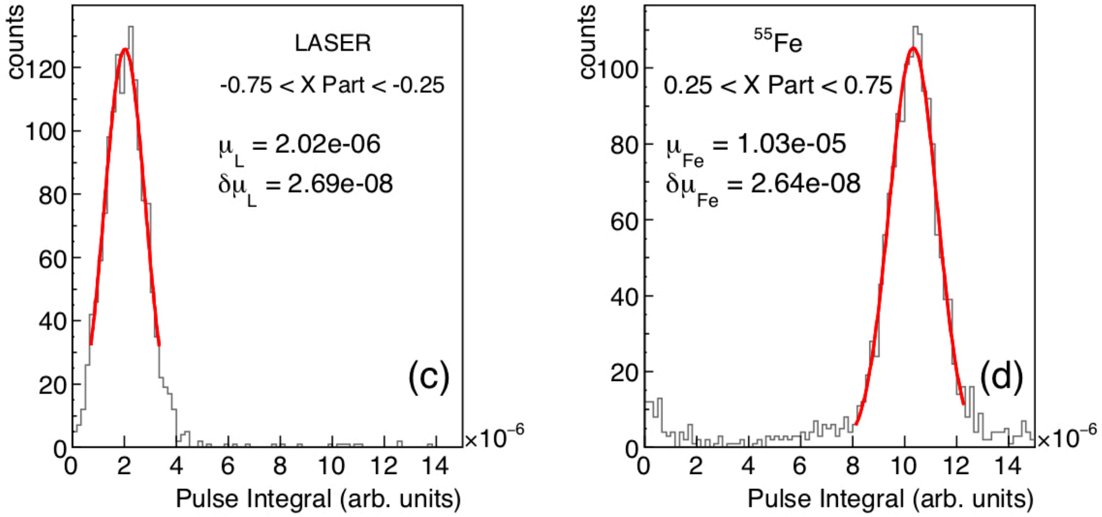


Laser energy calibration





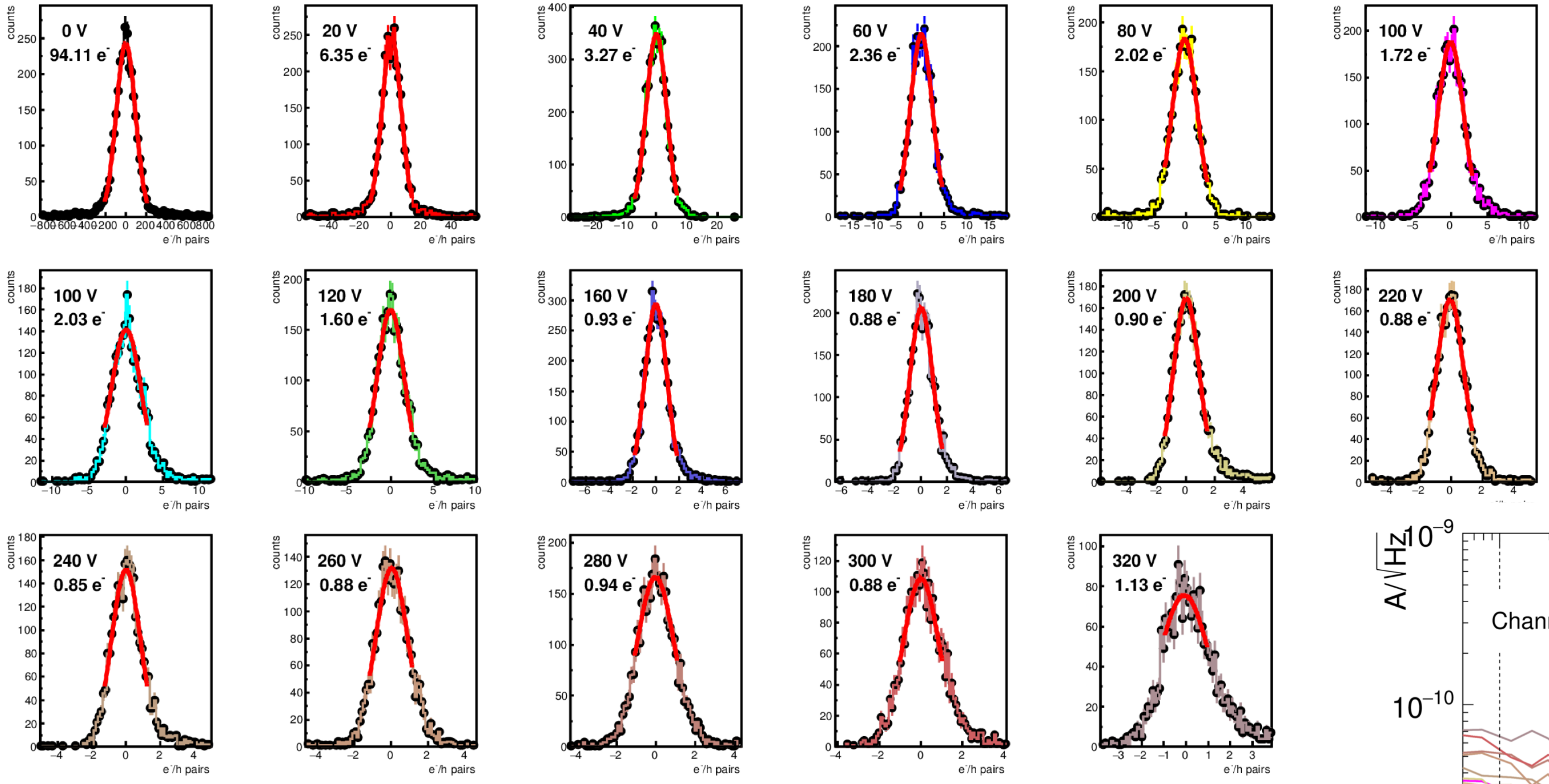


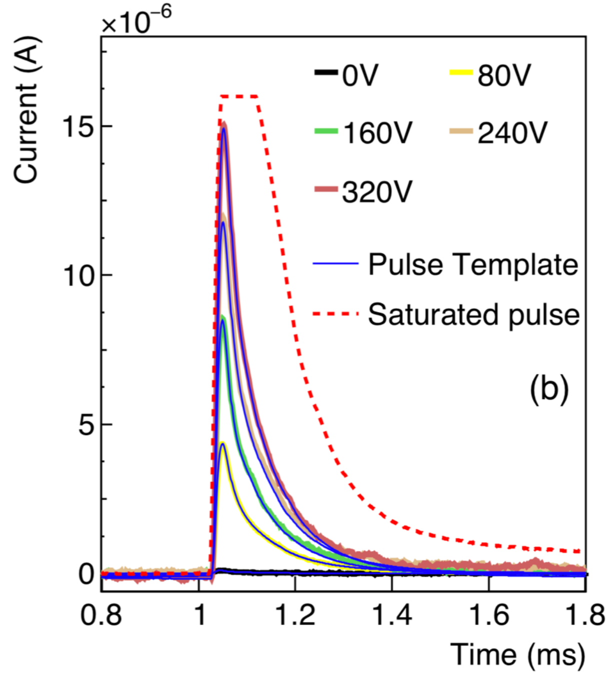


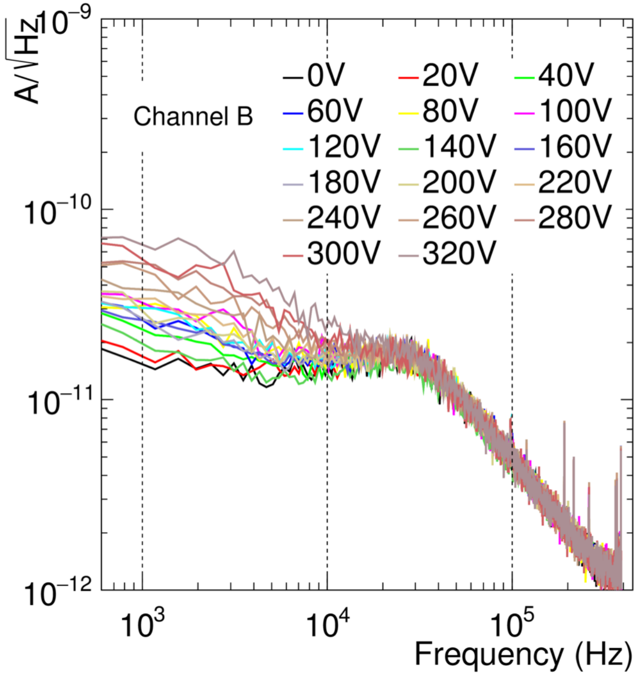
- Use 5.9 keV line of an ^{55}Fe source to calibrate the Laser energy.
- Laser beam and the ^{55}Fe sources collimated on two different spots.
- Use information in the phonon pulses to localize events.
- Adjust the laser amplitude for ~ 1 keV.
- Quantum yield for 1.9 eV laser photons significantly different than 5.9 keV.
- Doing the calibration at 0 V is important for energy calibration.

V. Iyer et al. e-Print: 2011.02234 [physics.ins-det]

Baseline resolution versus HV



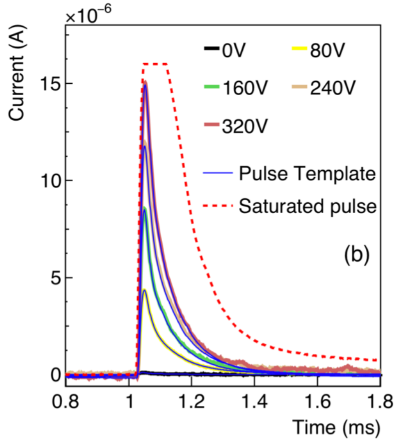


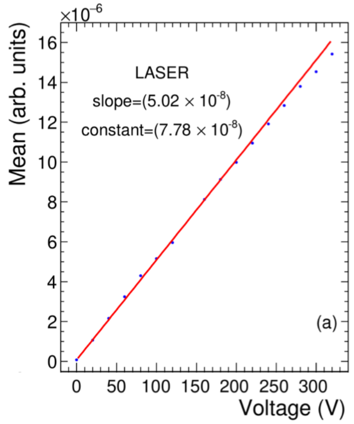


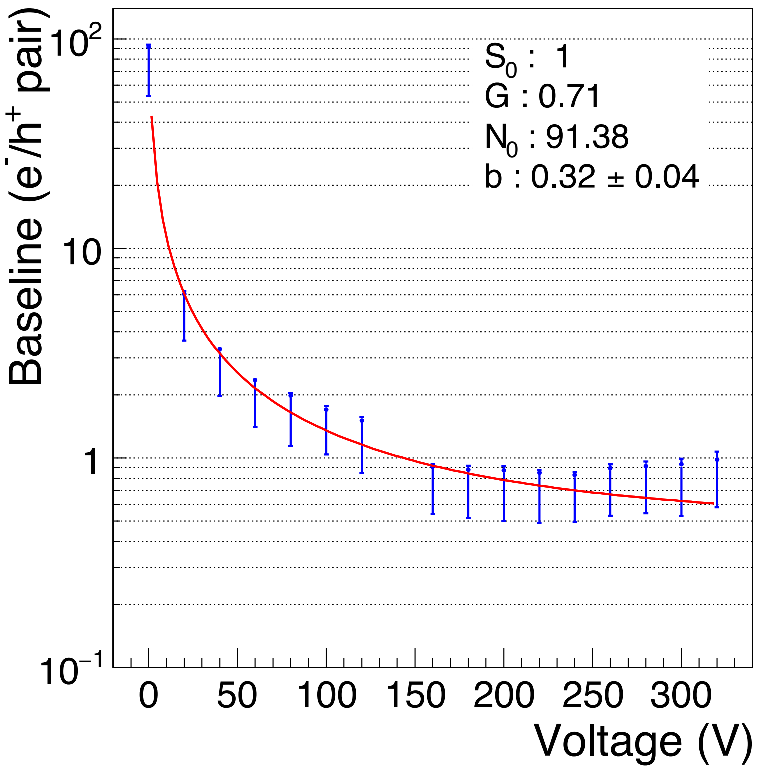
- Measured a linear increase of phonon signal amplitude with HV
- Noise increases ~ 100 V: Contribution from leakage.
- For HV>250 V observed nonlinearities likely due to the crystal heating.

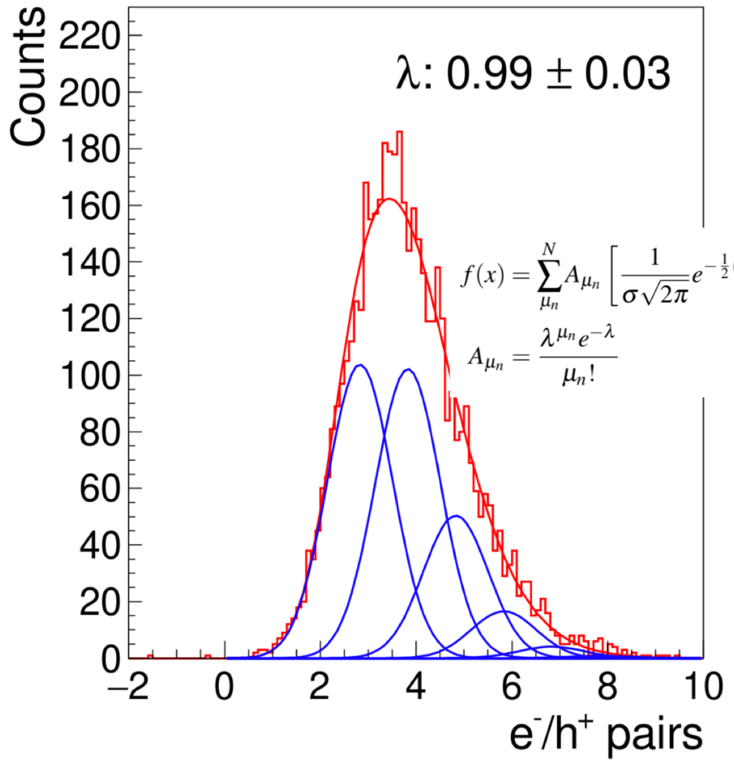
V. Iyer et al. e-Print: 2011.02234 [physics.ins-det]

Recent results with Si 100 g Si









$$f(x) = \sum_{\mu_n}^{N} A_{\mu_n}\left[\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu_n+s}{\sigma}\right)^2}\right]$$

$$A_{\mu_n} = \frac{\lambda^{\mu_n} e^{-\lambda}}{\mu_n!}$$

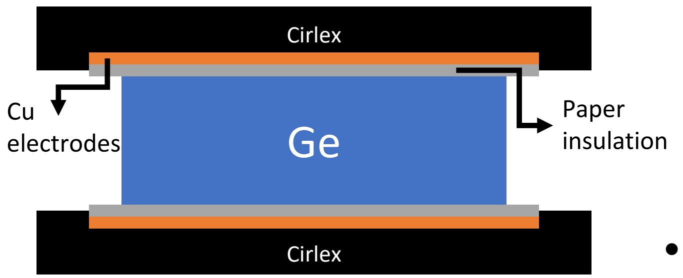
- Noise has two components: $N = \sqrt{N_0^2 + (Vb)^2}$
  - Sensor bias and readout: Independent of the HV
  - Leakge in the crystal: Linearly grows with HV
  - If $I_{leakage}$ is also a function of V => Noise increases as HV.I(V)

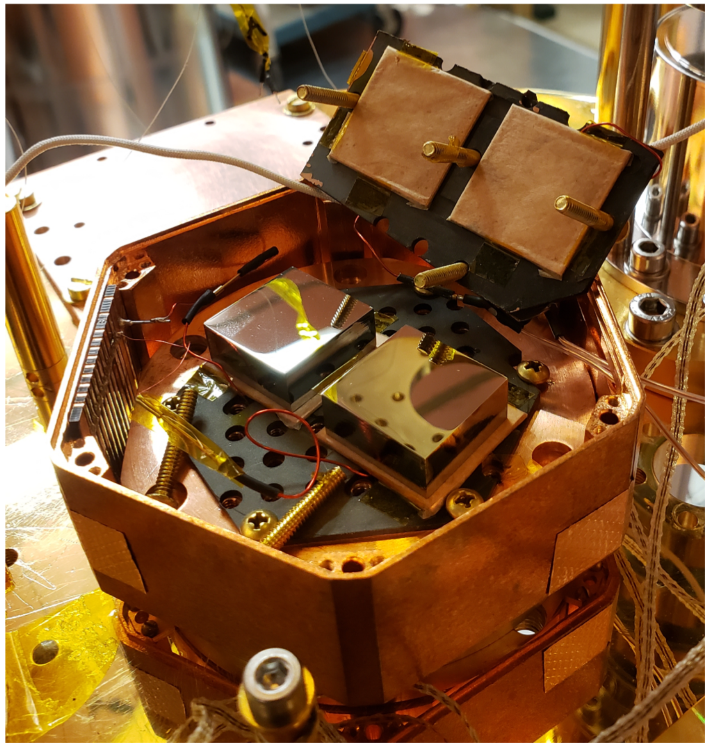
- Signal grows linearly with HV until: $S = S_0 + S_0 qVG/\varepsilon$
  - Signal so large that the TES nonlinearity becomes significant
  - Joule heating due to carrier drift => $T_{crystal}$ ↑

FIG. 5. The red histogram is the distribution of the total phonon energy measured in the detector when the LASER is incident on it. The red line is the Poisson-normalized multi Gaussian model given by Eq. 5, fit to the distribution. The blue lines are the Gaussians for different number of e^-/h^+ pairs produced by the LASER. The $\lambda = 0.99$ value represents the average number of e^-/h^+ pairs produced by the LASER.

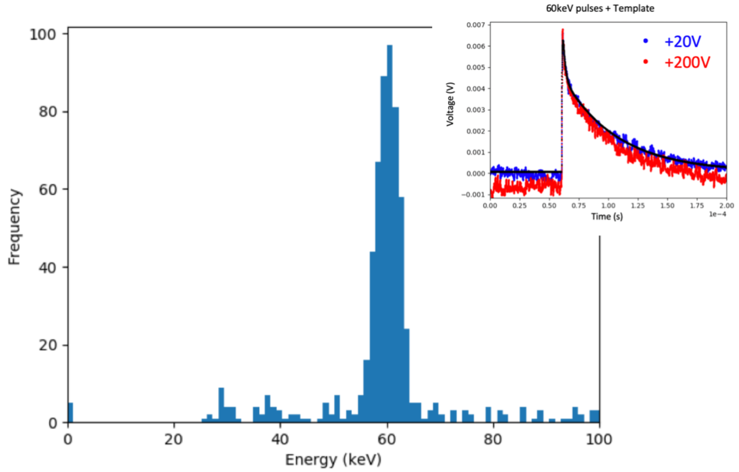
V. Iyer et al. e-Print: 2011.02234 [physics.ins-det]

Contact Free: Fast Crystal prescreening





- Ge crystals after minimal shaping processing
- Sandwiched between two metallic plates.
- A gap between the electrodes and crystal.
- Can readout ionization and check for gross leakage.
- Sensitivity to < 10^{-14} A Leakge with current CDMS readout.



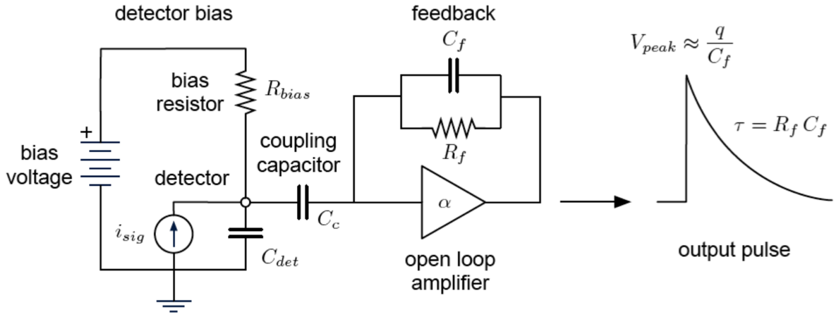
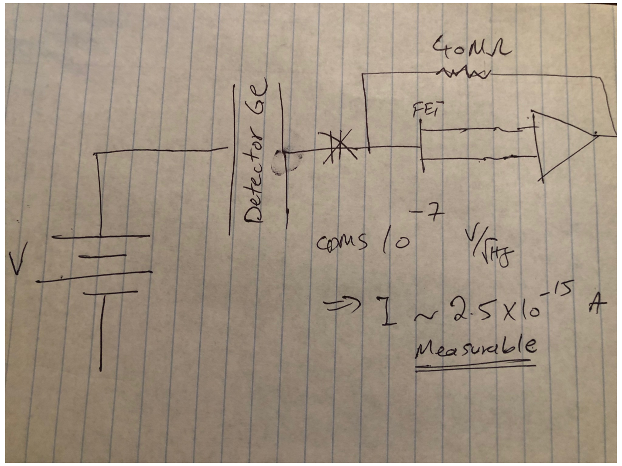
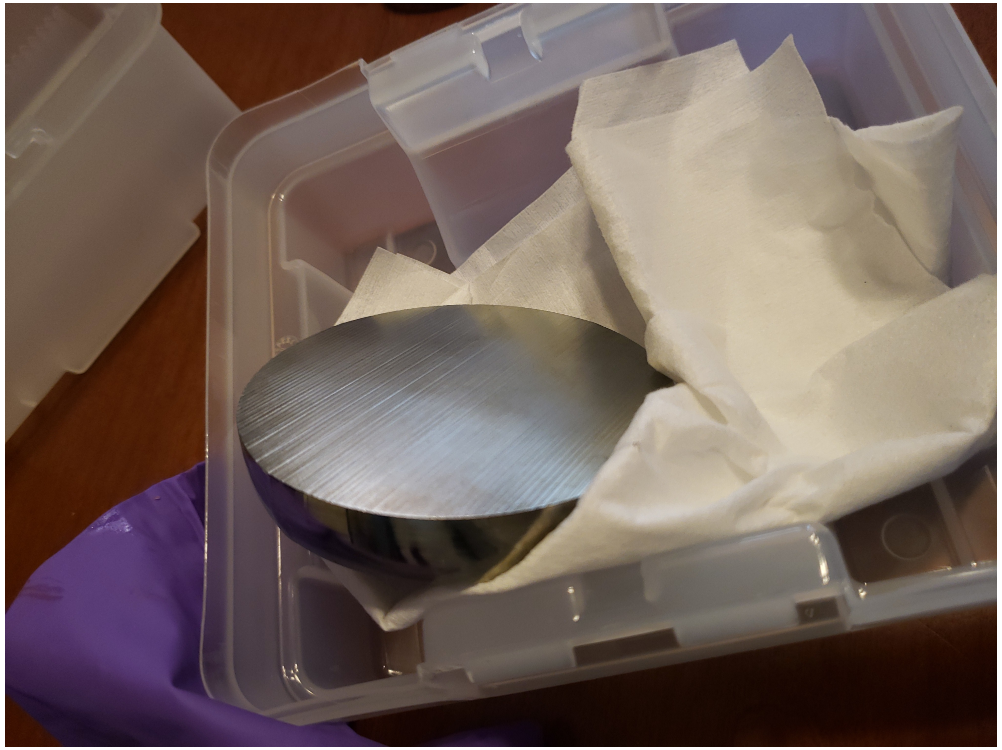
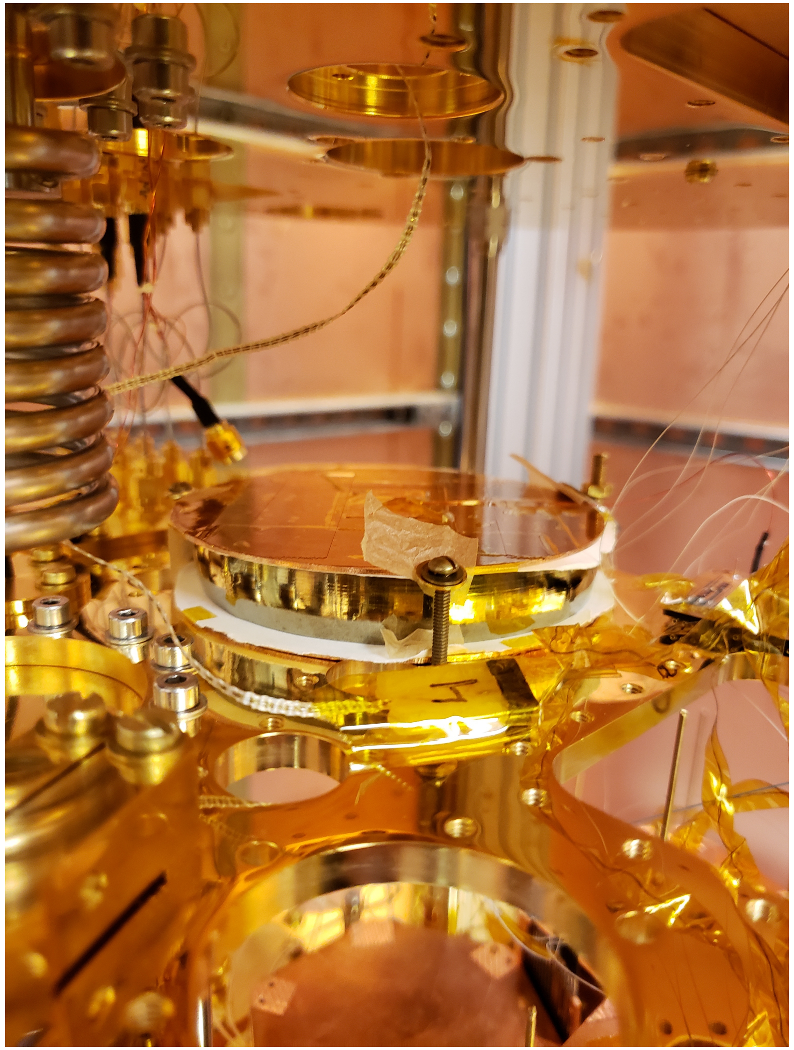


Figure 3.4: The basic charge amplifier topology.



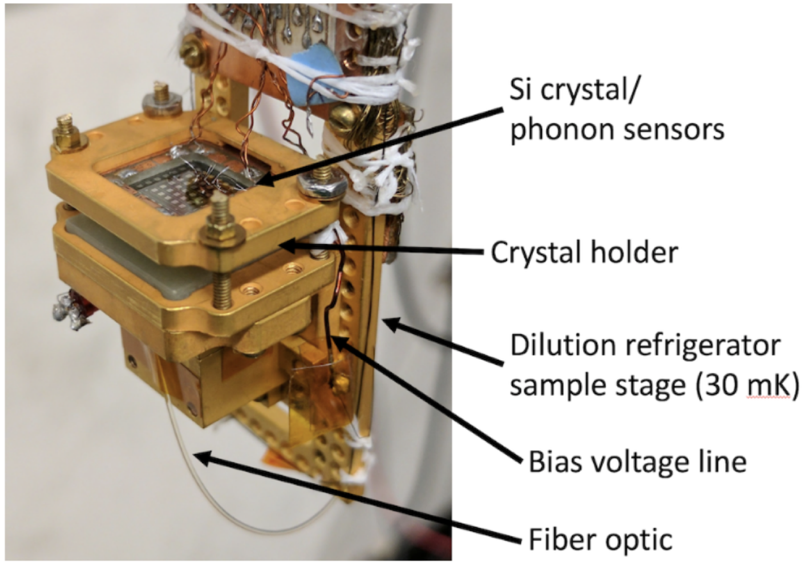
Large Ge smaple





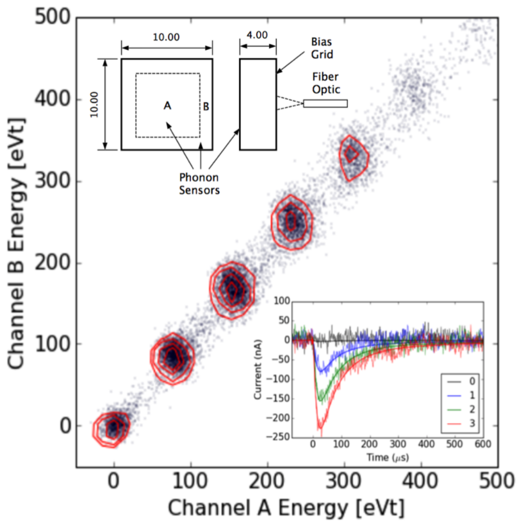
Φ=9 cm, h=1.5 cm ~ 700 g

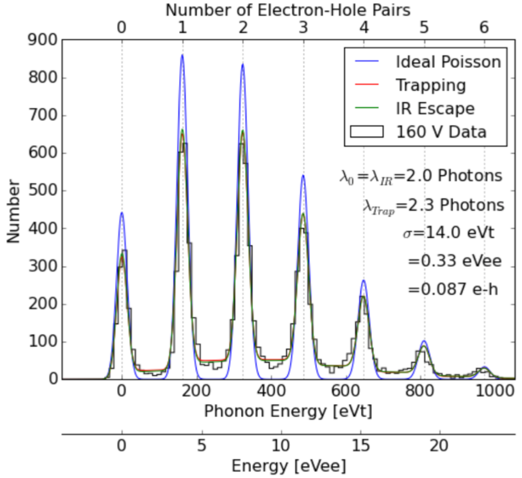
HVeV Single electron phonon mediated detectors



R. K. Romani et al., *Appl. Phys. Lett.* ***112***, *043501 (2018);*
https://doi.org/10.1063/1.5010699

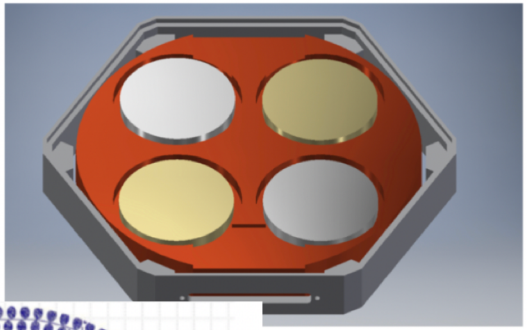
- Developed in Blas Cabrera group at SU
- Use 1 cm ^{2} 0.4 cm thick Si: ~ 1 g
- Use CDMS QET deisgn T_c~ 35 mK
- CDMS HV technology @ 160 Volts.
- Monochromatic Laser light: 640 nm
- Achieved ~0.1 e-h pair resoltion.
- **Clear single electron resolution!**

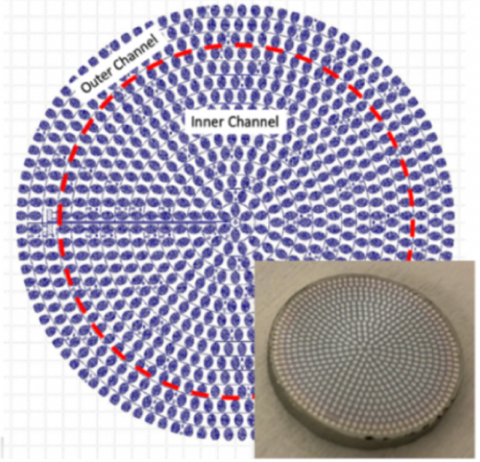




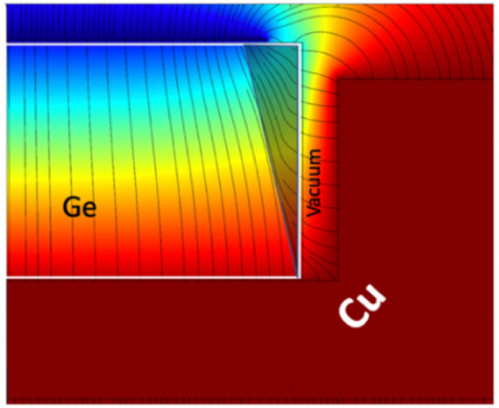
Next step with Smaller Si/Ge for single-electron sensitivity

- Produce smaller size detectors (10-20 g).
- Quantized ionization sensitivity.
- 4 Ge and/or Si samples per run.
- Samples are housed so that the fringe fields can be shaped.
- Detector phonon surface divided into an inner and outer (guard ring).
- New insulating contacts such as SiO_2 or amorphous Si to replace the vacuum.





ϕ=25mm
h=4 or 10mm

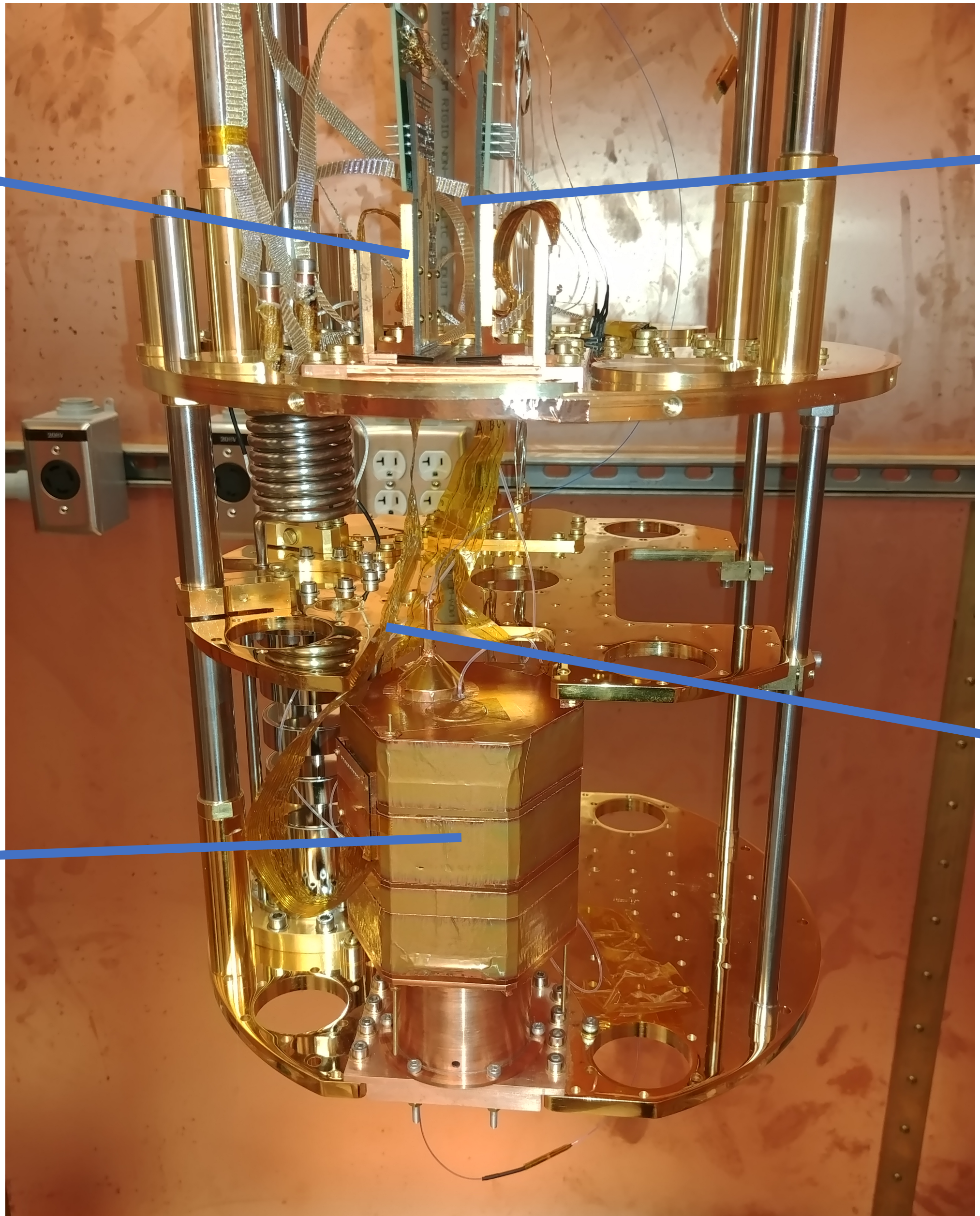


Questions

New Fridge, New wiring

8 SQUIDs installed on the Still plate

Be/Cu Twisted par wire bundles from 600 mK to RT

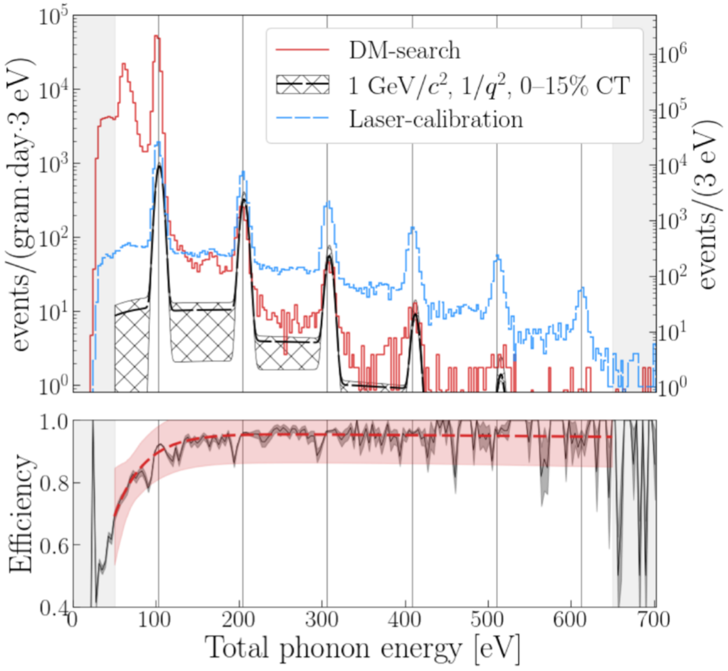


Detector stack mounted vertically without the tower structure

Flexible twsited Nb/Ti from detector to SQUET

Leakage in the single electron peaks

CDMS HVeV



SENSEI

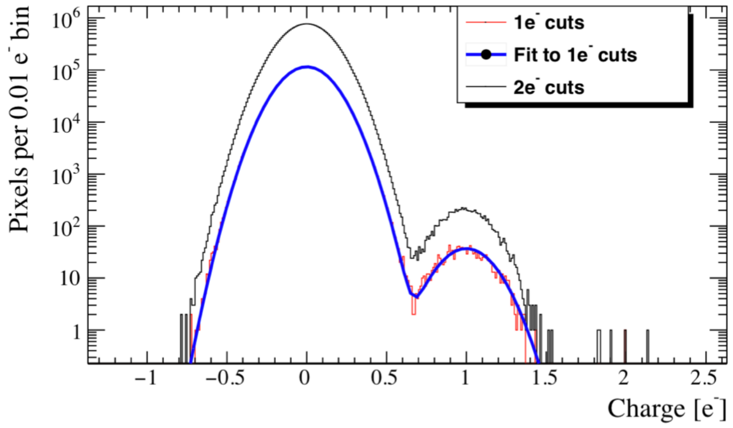


FIG. 3. The pixel charge spectra (after selection cuts) used for the 1 e$^-$ and 2 e$^-$ analyses. A double-Gaussian fit is shown for the spectrum with 1 e$^-$ cuts. There are no 3 e$^-$ or 4 e$^-$ events.

EDELWEISS

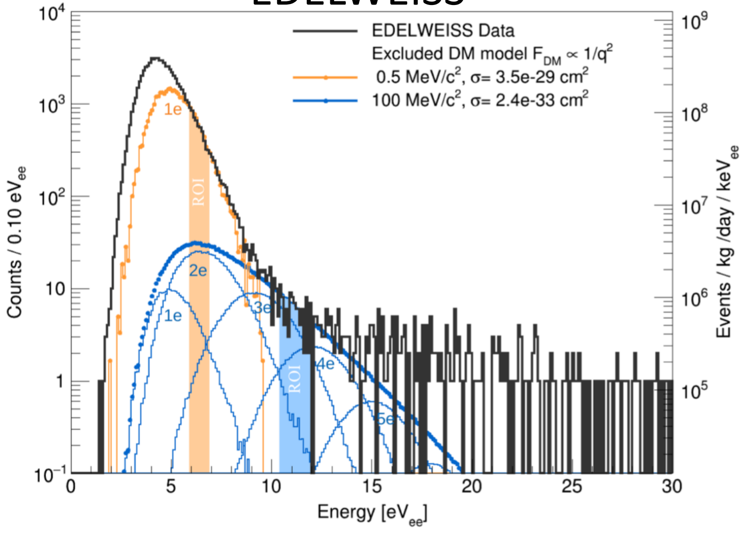


FIG. 3: Energy spectrum of the events selected for the DM search (black). The thick blue (orange) histogram is the simulation of the signal excluded at 90% C.L. for a DM particle with a mass of 10 (0.5) MeV/c^2, and $F_{DM} = 1/q^2$. The thin-line histograms of the same color represent the individual contributions of 1 to 5 electron-hole pairs. The corresponding ROIs used to set the upper limits are shown as shaded intervals using the same color code.

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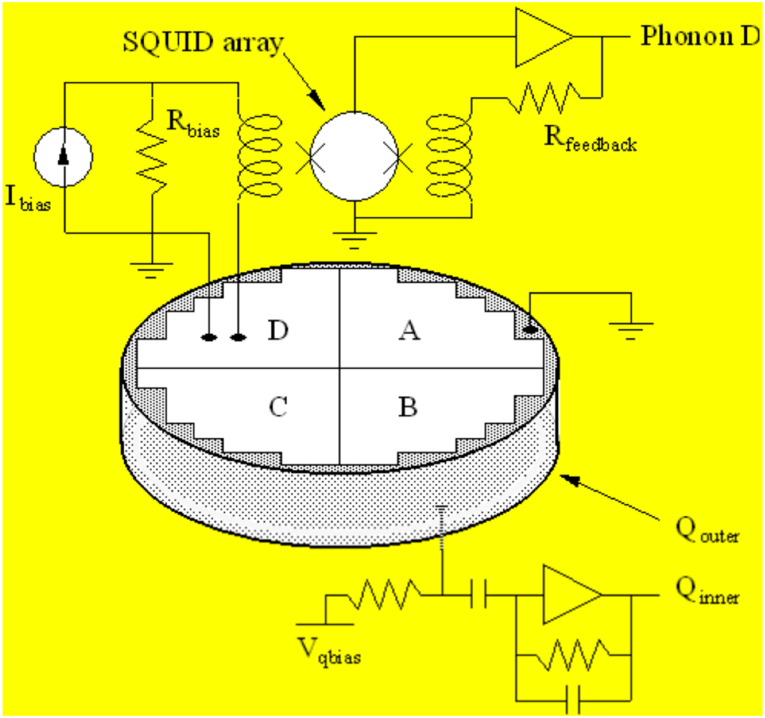
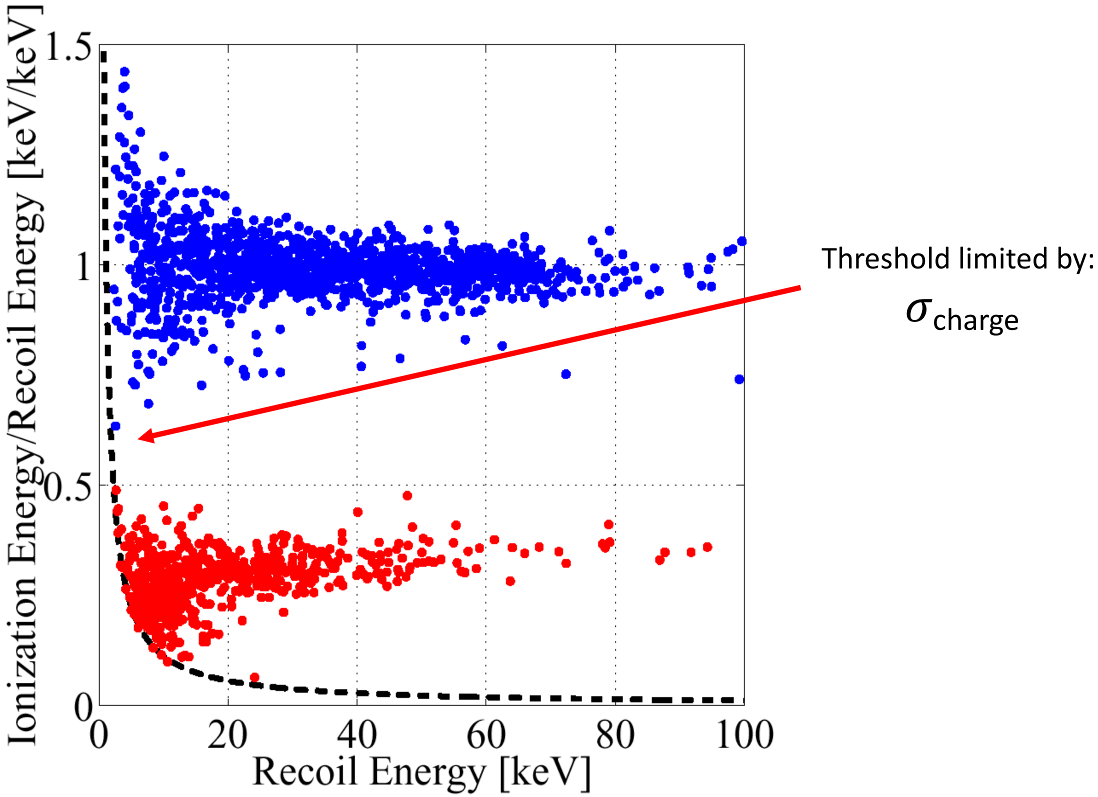
Phys.Rev.Lett. 125 (2020) 17, 171802

Phys.Rev.Lett. 125 (2020) 14, 141301

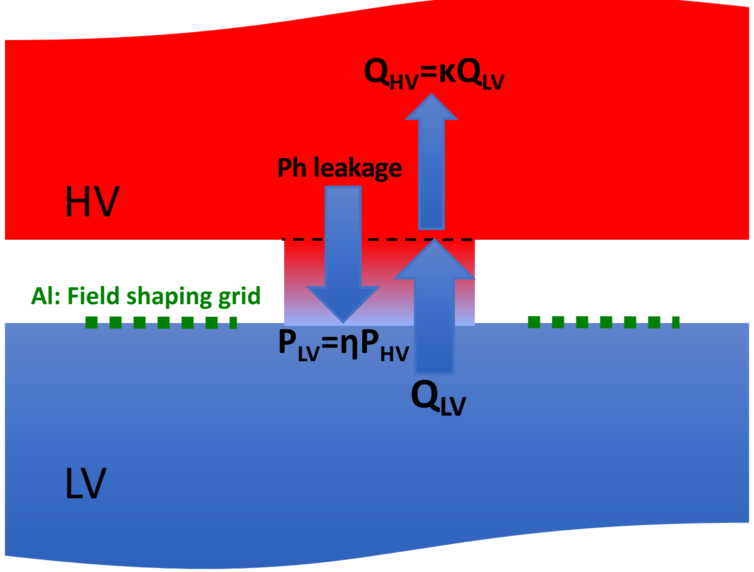
CDMS II event-by-event background discrimination

- Simultaneously measure ionization and phonon per each interaction in large Si or Ge (~ kg) crystals operating at T~20 mK.
- Superconducting Transition Edge Sensors (TES) cover one face.
- The other face covered by ionization electrodes: an inner electrode and a guard ring electrode.
- Use cold FET front-end to read charge and SQUIDs for phonon readout.
- Use ionization yield difference between electron recoil (ER) and nuclear recoil (NR) to discriminate WIMPS from background.
- Excellent discrimination for E_r> 10 keV . The threshold limited by ionization resolution.





TAMU event-by-event discrimination: HV-LV hybrid detector concept

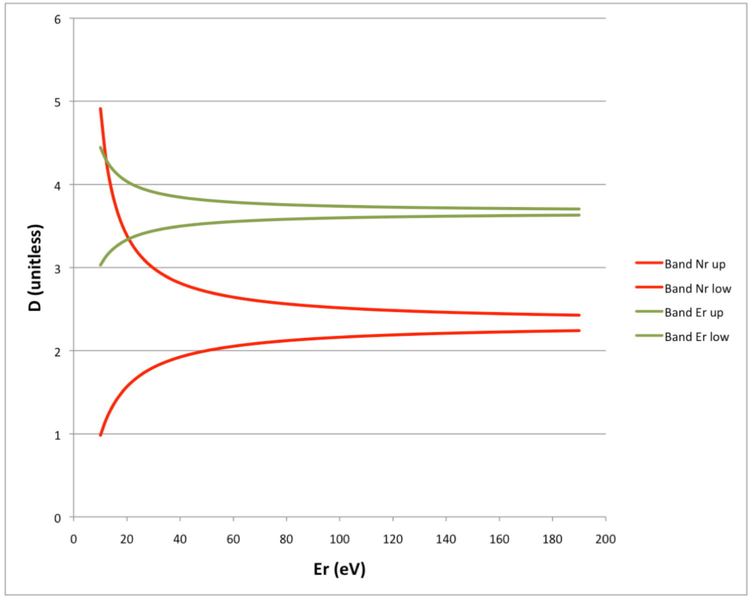


Ionization can be indirectly measured via NTL phonons
Recoil phonons: We prefer to have 0 Volts to minimize the NTL contribution

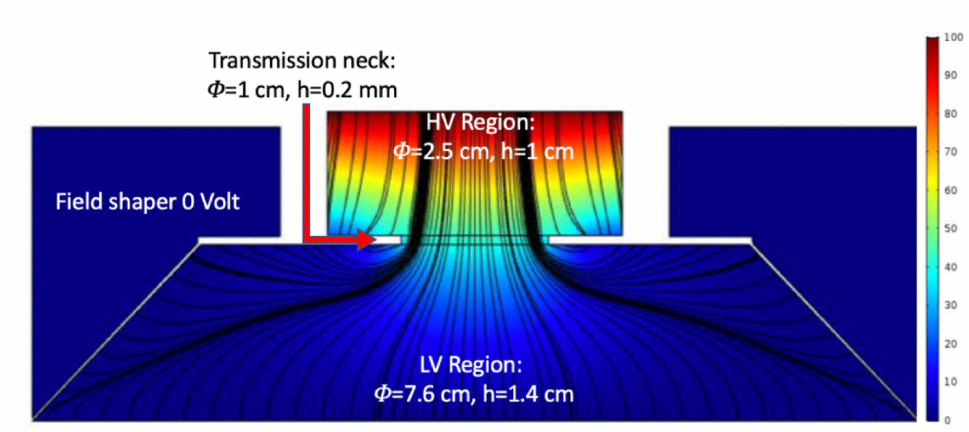
Soluiton:

- Combine both HV and LV in a monolithic crystal that is divided into two media through a restriction.
- Charge can be channeled using field shapers between the two media.
- Phonons are random so there is a geometric suppression proportional to 1/channel area.
- P_{HV}/P_{LV} to discriminate ER from NR.

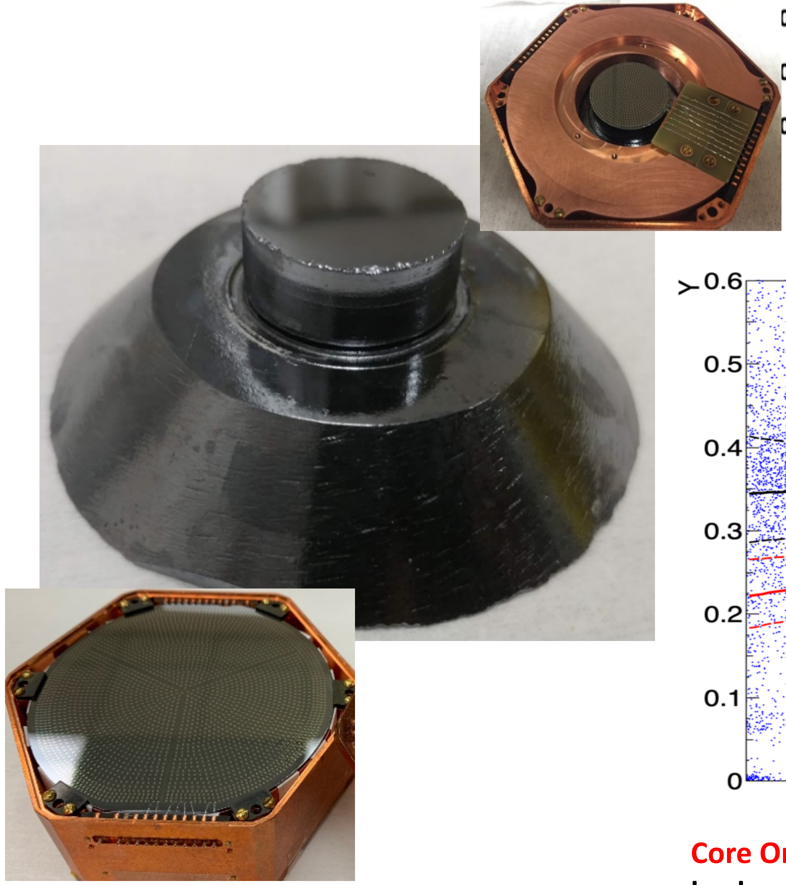
$$P_{HV} = \alpha[(1-\eta_{HL})E_R LV_{HV}/4 + \eta_{LH}E_R(1+LV_{LV}/4)]$$
$$P_{LV} = \beta[\eta_{HL}E_R LV_{HV}/4 + (1-\eta_{LH})E_R(1+LV_{LV}/4)]$$
$$\text{Discrimination}: D = \frac{P_{HV}}{P_{LV}}$$

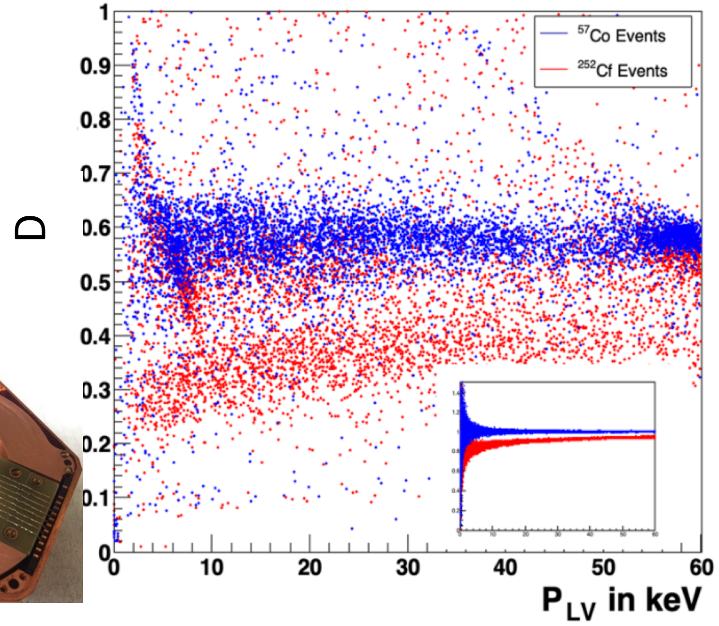


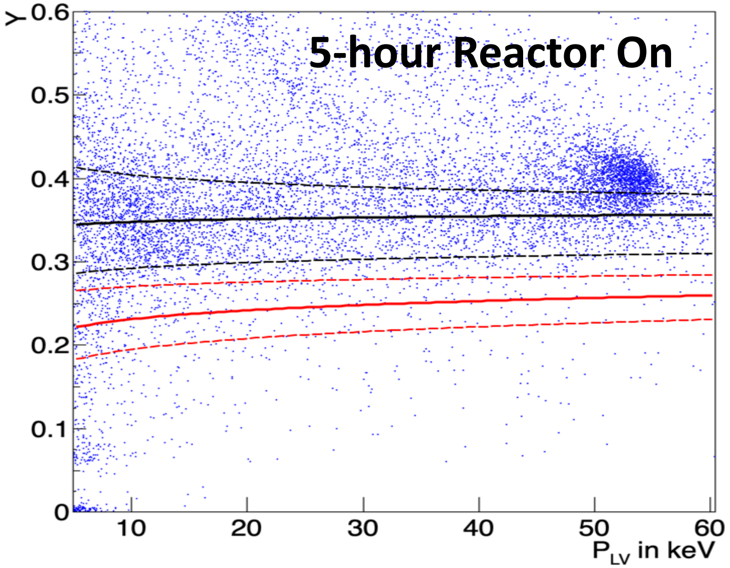
First TAMU hybrid prototype



- Si substrate shaped for the first hybrid prototype (100 g).
- Measured full charge transport from LV to HV regions.
- Phonon suppression matches model albeit being non-ideal.
- Observed clear discrimination between NR and ER calibrating with neutron source (^{252}Cf and ^{57}Co) and gamma sources.
- **Discrimination is more pronounced at low E_r**

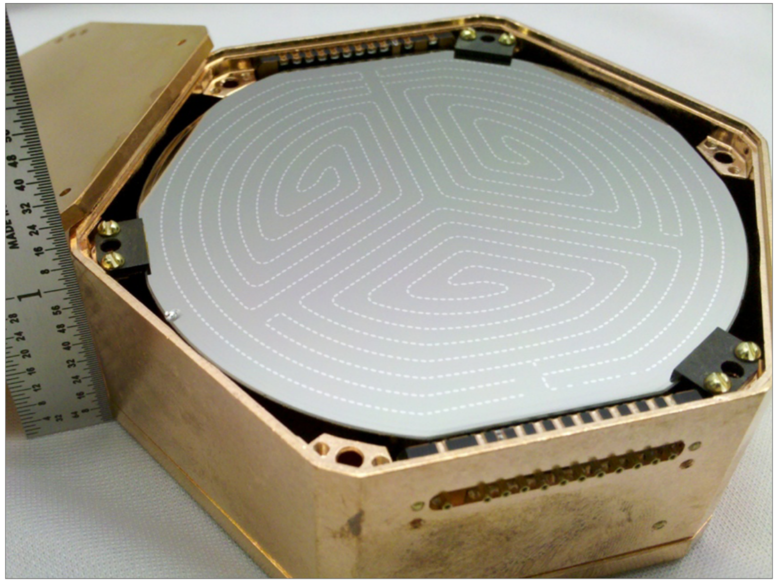


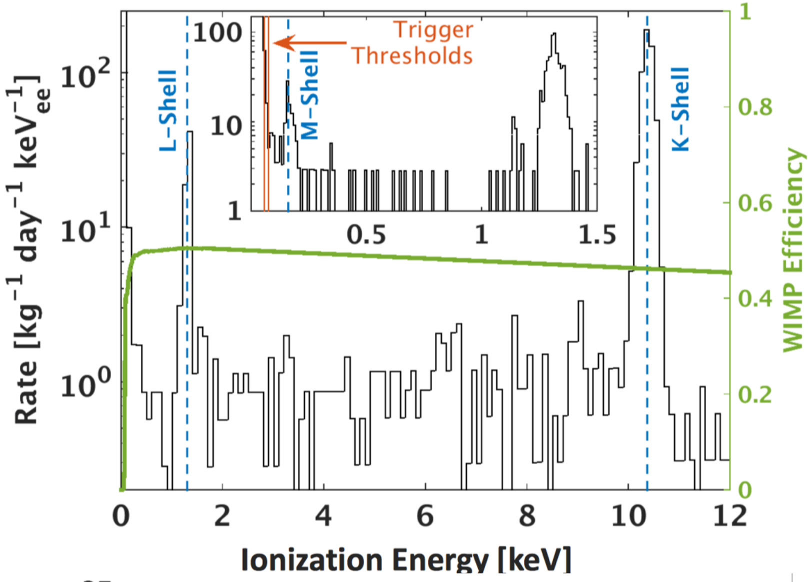


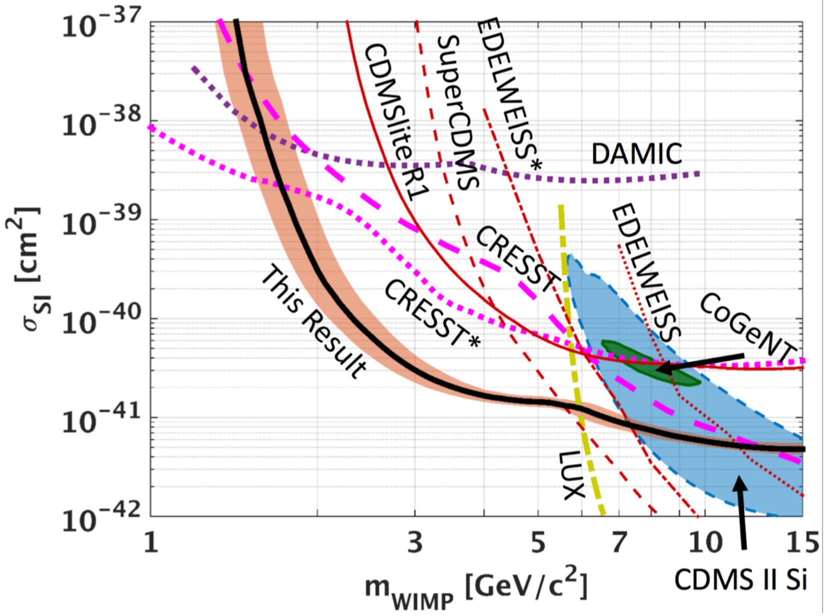


Core On: Raw count (ER+NR) ~340 DRU. NR band background without cuts ~20 DRU. Expect to reach DRU scale with full shielding, veto and analysis cuts.

CDMSlite: CDMS with phonon gain







- Use the Luke phonon amplification to indirectly measure ionization using very good phonon resolution.
- One iZIP (0.625 kg) used for this data
- ~70 kg.day exposure
- Impressive 14 eVee resolution for Vbias=69 Volts.

Limited to current leakage for V>70 Volts
Or E> 24 Volts/cm

Very low compared to standard 77K Ge detectors